TEXT FLY WITHIN THE BOOK ONLY

UNIVERSAL
LIBRARY

OU_166119

UNIVERSAL
LIBRARY

OSMANIA UNIVERSITY LIBRARY

Call No. Accession No.

Author

Title

This book should be returned on or before the date last marked below

THE MEASUREMENT AND CONTROL OF TEMPERATURES IN INDUSTRY

THE MEASUREMENT AND CONTROL OF TEMPERATURES IN INDUSTRY

BY

R. ROYDS, M.Sc., M.I.Mech.E.

CONSTABLE & COMPANY LTD
10-12 ORANGE STREET LONDON W C

LONDON

PUBLISHED BY
Constable and Company Ltd
10–12 Orange Street, W C.2

INDIA *and* PAKISTAN
Orient Longmans Ltd
BOMBAY CALCUTTA MADRAS

CANADA
Longmans, Green and Company
TORONTO

SOUTH *and* EAST AFRICA
Longmans, Green and Company Ltd
CAPETOWN NAIROBI

Printed in Great Britain by Butler & Tanner Ltd , Frome and London

PREFACE

SOME important developments have taken place in the standardisation, measurement and control of temperatures in industry since this book was first introduced under the title of *The Measurement of Steady and Fluctuating Temperatures.* These developments have necessitated much revision of the earlier volume, and it was felt that the new title more adequately describes the scope of the present book. The different methods and arrangements which are available for measuring temperatures are each best suited to a particular range and purpose, and are here described and discussed in turn. Greater attention is now directed to standardisation and to the automatic control of temperatures in industry. The thermometer or pyrometer is the sensitive element in all temperature controllers, and besides measuring the temperatures, the elements used may have to be adapted to operate in conjunction with the controllers. The signals received by the sensitive elements are usually too feeble to move the controlled medium effectively without being first mechanically or electrically magnified by the controller to give power enough for the purpose of control.

Special acknowledgments are due to The Institution of Civil Engineers and to The Institution of Mechanical Engineers for much technical information and for a variety of illustrations from their *Proceedings* ; to the National Physical Laboratory, of Teddington, and the National Bureau of Standards, of Washington, and to the several firms and other sources of information mentioned in the text, as well as to the many further particulars gleaned from sources too numerous to mention separately.

January 1951. R. ROYDS.

CONTENTS

CHAPTER		PAGE
	INTRODUCTION	1
I	STANDARD SCALES OF TEMPERATURE	3
II.	EXPANSION THERMOMETERS	10
III.	ELECTRICAL THERMOMETERS AND PYROMETERS	36
IV.	TOTAL RADIATION, OPTICAL AND PHOTO-ELECTRIC PYROMETERS	78
V.	GALVANOMETERS INDICATORS, RECORDERS AND CONTROLLERS OF TEMPERATURE	113
VI	VARIOUS OTHER PYROMETERS	176
VII.	THE MEAN TEMPERATURE OF A METAL WALL	184
VIII	THE MEASUREMENT OF RAPIDLY FLUCTUATING TEMPERATURES	215
APPENDIX		
I.	THE INTERNATIONAL TEMPERATURE SCALE OF 1948	243
II.	COMPARISON OF THERMOMETRIC SCALES	252
	INDEX	253

INTRODUCTION

WHEN heat has to be used in modern industry, one of the most important factors governing the effective control of the heating processes is the measurement of the temperatures with a reasonable degree of accuracy. Thermometers or pyrometers are used in many industries, as in the furnaces of steel, iron and other metal works, to assist in the production of the metals in the desired form and condition; in the cracking and distillation of oils; in the production of chemicals; in the manufacture of glass and refractories; in cement, pottery and brick kilns, varnish and enamel stoves, rubber preparation and vulcanisation; in breweries and distilleries; in power plant and in cold storage plant, various textile processes, and in numerous other industries. The automatic control or regulation of temperatures is also receiving increased application for the purposes of improving the quality and reliability of the product, of increasing the rate of production and the saving of heat and of labour. In important power plant, measurements of temperatures are undertaken for effective control of the operation and efficiency and reliability of the plant, usually under continuous working conditions. Important developments are likely to take place in power stations and on board ship because of the introduction of gas turbines; in the utilisation of low temperature heat for the heating of works and buildings; and in the manufacture of chemical and other products requiring low temperature heating or evaporation. Such plant needs to have effective temperature control. The converse problem of the internal cooling of works or buildings in hot climates, or during the summer season, is likely to receive more attention than formerly. An abnormal rise in the exhaust temperature from any cylinder of an internal combustion engine may be one of the first indications of an excessive consumption of fuel in that cylinder, either due to the cylinder taking too large a share of the load, or to a decrease in the thermal efficiency. The effective maintenance of thermal efficiency not only has an influence

on the economy of fuel, but may have an effect on the reliability of the plant, because a reduction of efficiency at a given load usually means that more heat has to be dissipated externally.

Temperature measurements are usually required when ordinary performance or acceptance tests are made on heating or cooling plant, or on heat engine installations, and it may be legitimate in some cases to include the measurement of losses of heat. Therefore the installation of thermometers and pyrometers in laboratories or in research stations often forms an important part of the equipment. In recent years most large firms or industrial and service establishments have devoted increased attention to the value of research work and in the formation of research associations. The various methods of measuring temperatures are being applied, with perhaps special designs or arrangements suitable for the problems in hand, such as are dealt with in Chapters VII and VIII.

THE MEASUREMENT AND CONTROL OF TEMPERATURES IN INDUSTRY

CHAPTER I

STANDARD SCALES OF TEMPERATURE

THE word temperature signifies the degree of hotness or the intensity of the heat in a body, measured according to some chosen scale. The most suitable method of measuring temperature usually depends upon a multitude of circumstances, but it is evident that, whatever method is adopted, it is desirable to have a common scale of measurement, or at any rate, if more than one scale is used there should be a definite relationship between them. Experience has shown that the melting point of ice and the boiling point of water can be reproduced with great exactitude under definite conditions, and the ease with which "pure" water can be obtained has led to the range between these two points being adopted as the Fundamental Interval to which all measurements of temperature are referred.

The "freezing point," as the lower fixed point is called, is usually determined by placing the instrument or "thermometer" in a vessel surrounded by finely broken pure ice from which the water is dripping, as represented in Fig. 2. The boiling point is determined by placing the thermometer in the saturated steam coming from "pure" boiling water with the pressure at one standard atmosphere * in the manner shown in Fig. 3, p. 12.

The most common scale of measurement used by English-speaking engineers is the Fahrenheit scale, where the freezing point is called 32 degrees (32° F.) and the boiling point 212

* Refer to p. 244 for definition.

degrees (212° F.). Thus the range from the freezing to the boiling point is 180°. The Centigrade or Celsius scale is often used by English-speaking engineers, but more generally by physicists and chemists, and also by engineers and industrialists on the Continent of Europe. The freezing point is called 0 degrees (0° C.) and the boiling point 100 degrees (100° C.). Thus a change of temperature of 1° F. is equivalent to a change of $\frac{100}{180}=\frac{5}{9}°$ on the Centigrade scale. Thus, temperature in degrees Cent. = (deg. Fahr. -32) $\times\frac{100}{180}$. An easily remembered rule to convert from deg. Fahr. to deg. Cent., or vice versa, is to add 40 to the temperature reading, multiply by $\frac{5}{9}$ or by $\frac{9}{5}$ as the case may be, and then subtract 40. A convenient table for conversion of these scales is given on p. 252.

For practical use a thermometer needs to be graduated in degrees of temperature, and whatever may be the type of thermometer the reading should be definite and invariable if true temperatures are to be recorded. It is known, for instance, that mercury does not expand at quite a uniform rate with increase of temperature, although a mercury thermometer usually has the degree divisions equally spaced along the stem. Most other substances have similar defects and involve similar discrepancies. Thus, even though the freezing and boiling points might be correctly recorded by different types of thermometers, it does not follow that the intermediate readings would agree, and it becomes necessary therefore to have some definite standard of comparison.

The zero points on the ordinary scales of temperature referred to previously were originally fixed because of their general convenience and without considering their relationship to what is called "the absolute zero" of temperature. Although the absolute zero of temperature has never been actually reached, its value in relation to the ordinary scales of temperature has been accurately determined by indirect means.

Standard Thermodynamic Scale of Temperature.—The necessity for some standard scale led Lord Kelvin in 1848 to propose the thermodynamic scale, based upon the Carnot cycle * for heat engines. On this theoretical cycle a quantity

* For a detailed description of this cycle, reference may be made to any standard textbook on "Heat" or "Heat Engines."

of heat Q_1 is supposed to be taken in by the working substance at the absolute temperature τ_1, and the quantity of heat Q_2 rejected at the absolute temperature τ_2. It can be shown that, no matter what the working substance may be,

$$\frac{Q_1}{Q_2} = \frac{\tau_1}{\tau_2}$$

or,

$$\frac{Q_1}{\tau_1} = \frac{Q_2}{\tau_2} \quad . \quad . \quad . \quad . \quad (1)$$

It will be noted that if Q_2 were zero the value of τ_2 would also be zero, that is, the "absolute zero of temperature." Temperatures on the absolute scale in deg. Cent. are sometimes distinguished by the letter K.

It can also be shown that if a Carnot cycle engine works between the temperature limits of 100° C. and 0° C., then for every 373 units of heat put in at 100° C. it will turn 100 units into work theoretically and reject 273 units at 0° C. The ratio of these temperatures on the thermodynamic scale is therefore 373 : 273, and thus the freezing point would be 273 degrees on this absolute scale.

Experience has shown that it is practically impossible to carry out the Carnot cycle completely, and thus, while the idea of the cycle is a useful conception, no practical thermometer can be constructed to use the Carnot cycle directly. It can be proved, however, that an equivalent measure of temperature is given by the expansion of a perfect gas with increase of temperature,* and as there are the gases, hydrogen, nitrogen, oxygen, etc., which nearly obey the laws of perfect gases, such can be used to give a standard measure of absolute temperature. The characteristic equation expressing the fundamental law of a perfect gas is

$$PV = RT \quad . \quad . \quad . \quad . \quad (2)$$

where P = absolute pressure ; V = absolute volume ; T = absolute temperature, and R is a constant depending only upon the units adopted and the mass of perfect gas under consideration. Although the previously mentioned "permanent" gases follow this law fairly closely under ordinary conditions,

* See Preston's *Theory of Heat.*

the value of $R=\frac{C}{M}$, where M is the number of pounds of gas equal to the molecular weight, and C=1542 when expressed in ft. lb. deg. Fahr. units.

Thus if P_1, V_1, T_1 represent the pressure, volume and temperature of a certain mass of perfect gas under one condition, and P_2, V_2, T_2 represent the above relations of the same mass of perfect gas under other conditions, then,

$$\frac{P_1V_1}{T_1}=\frac{P_2V_2}{T_2}=R.$$

If $V_1=V_2$, then, $$P_1-P_2=\frac{R}{V_1}(T_1-T_2) \quad . \quad . \quad . \quad (3)$$

i.e. if the volume is kept constant the change of pressure is a measure of the change of temperature.

Again, if the pressure be kept constant at the value P_1, then,

$$V_1-V_2=\frac{R}{P_1}(T_1-T_2) \quad . \quad . \quad . \quad (4)$$

i.e. at constant pressure the change of volume is a measure of the change of temperature.

Regnault found that the constant volume gas thermometer was more accurate in use than one at constant pressure. Fig. 1 shows in outline the apparatus adopted in his experiments. The bulb A was filled with pure dry air at a pressure of 760 millimetres of mercury and was connected to the manometer tube BC. When the temperature of the bulb A was increased the mercury in the leg B was kept at a constant level O by pouring mercury into the leg C. The difference of level *h* is a measure of the increase in the temperature of the bulb A from some standard condition. The thermometer would be calibrated by immersion in ice for 0° C. and in steam at normal atmospheric pressure for 100° C.

According to Regnault, if P_{100} is the absolute pressure of the air in the bulb at 100° C. and P_0 that at 0° C., then for air,

$$P_{100}=1{\cdot}3665P_0 \quad \text{(volume constant)},$$

$$\therefore \text{ from eqn. 3, } P_0\times 0{\cdot}3665=100\frac{R}{V_0}$$

or,
$$\frac{V_0}{R}=\frac{272{\cdot}85}{P_0}$$

Thus any temperature $t°$ C. on this scale would be given by

$$t = T - T_0 = \frac{V_0}{R}(P - P_0)$$

$$= 272{\cdot}85\left(\frac{P}{P_0} - 1\right)$$

If $T = 0$, then $P = 0$ and $t = -T_0 = -272{\cdot}85°$ C., and this there-

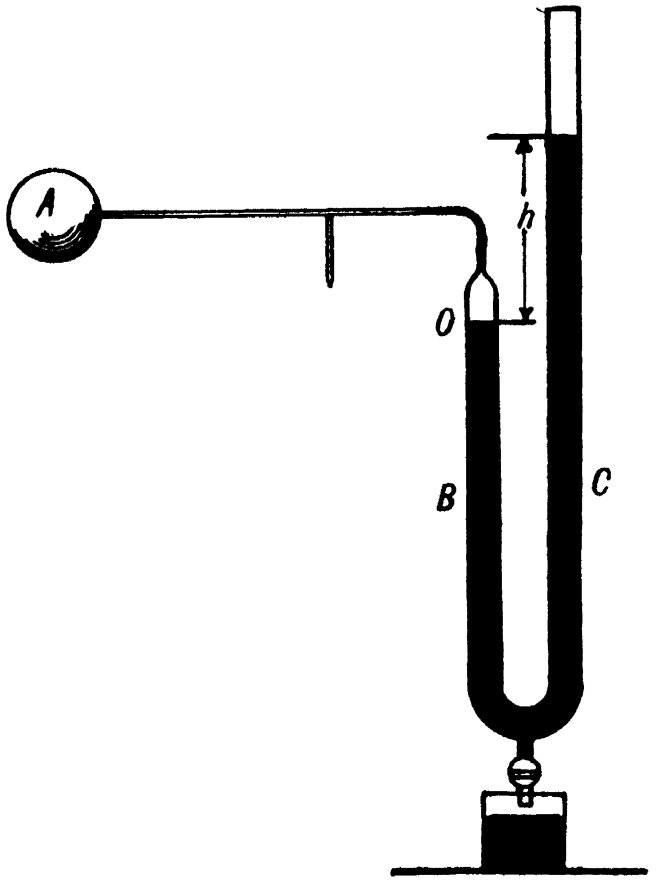


FIG. 1.—Constant volume gas thermometer.

fore represents the absolute zero of temperature on this scale. Dry air, however, does not quite follow the laws of a perfect gas between 0° C. and 100° C., but hydrogen has been found to behave very nearly as a perfect gas between these temperatures. Calculations based upon the physical properties of hydrogen gas show that the corrections necessary to bring

the hydrogen gas thermometer into agreement with the thermodynamic scale are no greater than the experimental errors involved in gas thermometry. According to the calculations of the late Professor Callendar * the corrections to be made to bring the hydrogen scale into unison with the thermodynamic scale are not greater than about +0·044° C. at 1000° C. and are much less than this from −100° C. to 500° C. The absolute zero of temperature is found to be very near the value −273° C. (−460° F. nearly).

The hydrogen thermometer with an iridio-platinum bulb can be used up to about 500° C. If the temperature is much above this the hydrogen is liable to pass through the iridio-platinum bulb. Porcelain is gas-tight to over 1000° C. if glazed, but the glaze begins to melt at about 1100° C. Also at high temperatures hydrogen has some slight action on porcelain. On account of these difficulties nitrogen is more often employed in gas thermometry for high temperatures. Messrs. Holborn and Day have used such a thermometer up to 1300° C. (2372° F.). The corrections for nitrogen in reducing the readings to the thermodynamic scale are rather larger than for hydrogen, being, according to the late Professor Callendar, +0·65° C. at 1000° C. For accurate measurements certain small allowances are necessary on account of the expansion of the bulb and the change in the temperature of the gas in the tube connection between the bulb and the manometer. These special arrangements of the gas thermometer are not generally convenient for ordinary measurements of temperature and are to be regarded as standards for purposes of reference.

The experimental difficulties incident in the practical realisation of the thermodynamic scale have made it expedient to adopt a practical scale, designated the International Temperature Scale, conforming with the thermodynamic scale as closely as is possible with present knowledge. The specification of this scale was adopted provisionally at the Seventh General Conference of Weights and Measures of the Bureau International des Poids et Mesures in 1927. A revised text was published as an appendix to the proceedings of the Eighth General Conference (*Trav. Bur. int. Poids Mes.*, 1934, 19).

* *Phil. Mag.*, January, 1903.

The text of the International Temperature Scale, 1927, is given in *The Units and Standards of Measurement employed at the National Physical Laboratory* and of the scale as revised in 1948 in a pamphlet entitled "The International Temperature Scale of 1948." Both are published through the National Physical Laboratory by H.M. Stationery Office. The more important features of the 1948 scale are given in Appendix I, p. 243.

The actual method of measuring temperature in practice depends primarily upon the temperature to be measured and on the degree of accuracy required, as well as on the general convenience of the method for the particular purpose. The mercury thermometer, for instance, may be well suited for moderate temperatures of a steady character, but is not of much use in measuring the instantaneous values of rapidly varying temperatures such as may occur at the working surfaces of engine cylinders or pistons. Nor is the mercury thermometer practicable where the space available is very limited, as, for instance, in the metal of an ordinary condenser or boiler tube.

The principal methods adopted to signify or to measure temperatures or changes of temperature depend upon the following physical properties of matter:

1. The expansion of solids, liquids or gases.
2. The vapour pressure of liquids.
3. The electrical resistance of metals.
4. The thermo-electric potential between two dissimilar metals.
5. The intensity or the amount of total radiation from a hot body.
6. The intensity or the amount of light emitted by a hot body.
7. The comparison with known melting or freezing points of selected substances and the known boiling points of selected liquids.

In subsequent chapters it is proposed to consider in some detail the more important features of these various methods.

CHAPTER II

EXPANSION THERMOMETERS

THE expansion of a suitable liquid is commonly used to indicate temperature. Mercury in glass is most generally suitable on account of its fairly regular expansion with increase of temperature, and it can be used over a comparatively large range, the freezing point of mercury being $-38{\cdot}87°$ C. and its boiling point at normal atmospheric pressure $356{\cdot}58°$ C. (about $674°$ F.). Its low specific heat and high conductivity also enables it to acquire readily the temperature of the surroundings. Such liquids as alcohol, ether, etc., possess a larger coefficient of expansion, a higher specific heat and a lower specific gravity than mercury, but they are not generally suitable for the measurement of the temperatures commonly dealt with by engineers and industrialists generally because of the comparatively low boiling points of these liquids.

Although an engineer would hardly ever be called upon to construct a mercury thermometer, a brief description of the methods in use may assist one to realise some of the difficulties attending the accurate measurement of temperature. In making a mercury glass thermometer a capillary tube of uniform bore would have a bulb of suitable size blown or attached at one end. The uniformity of the bore could be tested by drawing in a short thread of mercury to different positions in the tube, and if this thread were found to be practically of uniform length at the various positions in the tube it would follow that the bore was fairly uniform. If appreciable differences of length occurred the tube would be rejected. The tube and bulb would be cleaned in boiling nitric acid to remove all organic matter. The empty bulb would sometime afterwards be heated to expel some of the contained air and the open end of the tube then dipped under the surface of clean dry mercury so that, as the bulb cools, some mercury is forced into the tube and bulb. To fill the bulb completely the mercury thus introduced is heated to

expel all the air, the bulb and tube being then filled with mercury and its vapour. Dipping the end below the surface of the mercury, and allowing the bulb to cool, the mercury then enters the tube as the vapour condenses and completely fills the instrument. Some difficulty may be experienced in getting rid of all the air, as minute bubbles are liable to attach themselves to the sides of the glass and are sometimes difficult to dislodge. When the bulb and tube or stem are filled completely the instrument is raised to the region of the highest temperature to be measured and the end hermetically sealed while in this state. To prevent the bursting of the thermometer should it be accidentally raised afterwards to a temperature beyond its range, it is usual to have the upper end of the tube widened out before sealing, and this in practice is often found to be a necessary precaution. If the size of the bulb and stem have been suitably arranged the bulb and the lower part of the stem would be filled with mercury at the lowest temperature intended to be measured.

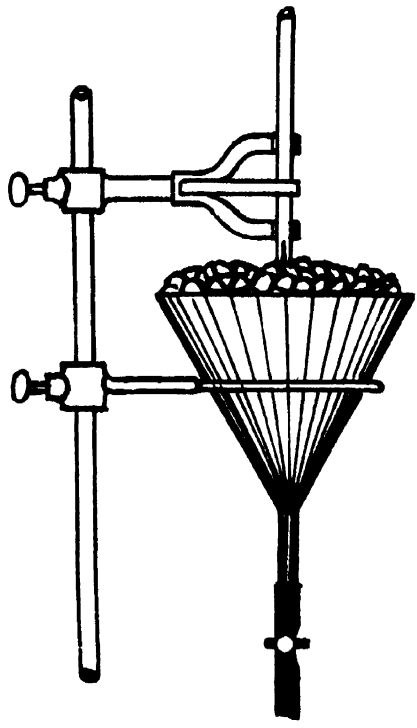


FIG. 2.—Determination of freezing point.

For actual use, of course, it is necessary to mark a scale on the stem of the thermometer and it is usual to mark the two fundamental points, i.e. freezing and boiling points, before graduating the stem. A common arrangement for the determination of the freezing point is shown in Fig. 2. The thermometer is supported as shown with the bulb and part of the stem surrounded with finely broken pure ice with the thread of mercury just exposed to view. Ordinary commercial ice manufactured from clean water is usually sufficient for the purpose when well washed. The melted ice is allowed to drip

slowly from the funnel. If impure ice only is available the thermometer might be placed in a test tube containing pure water and the test tube surrounded with the ice. In this case the water would begin to freeze and would eventually arrive at the freezing point. In due course the reading of the thermometer would become constant and this position would be marked on the stem as the freezing point. It should be noted, however, that for work of the highest precision it is recommended on the International Temperature Scale of 1948, referred to on p. 246, the zero point be realised by means of the triple point of water.

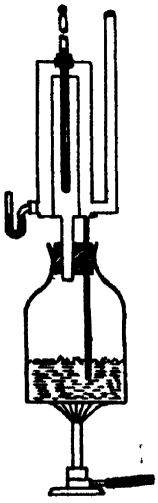


FIG. 3.—Determination of boiling point.

The boiling point is determined by placing the bulb and column of mercury in contact with steam at the standard atmospheric pressure.* A suitable apparatus called a "hypsometer" is represented in Fig. 3 and is self-explanatory. The thermometer is placed as shown quite clear of the boiling water so that the top of the column of mercury is just exposed to view. When the reading becomes constant the stem is marked provisionally, and this would correspond to 100° C. (212° F.) provided the pressure was at the standard value. This involves the correct reading of the barometer, and if the absolute pressure of the steam differs from the standard an allowance should be made in accordance with the expressions given on p. 248. The correct position on the stem is then marked. It is desirable, of course, to choose the boiling point determination when the barometer is steady. When aiming at the highest degree of accuracy, barometer corrections may be made to allow for latitude and the altitude above sea level, for these affect the value of gravitational acceleration and of the density of the mercury in the same proportions. An allowance should also be made for changes in the density of the mercury, and in the height or length of the barometer scale due to linear expansion with rise of temperature. It is usual to divide the stem of the thermometer between the freezing and boiling points into equal divisions.

* See p. 244 for definition.

It was mentioned on p. 8 that the thermodynamic scale has been adopted as the standard of reference. Mercury thermometers, when compared with this standard, are liable to certain inaccuracies, the importance of which depend to some extent upon the degree of accuracy required in using the thermometer. Generally speaking, engineers in practice do not require the same degree of accuracy in measuring temperatures as the physicist or chemist working in the laboratory, mainly for the reason that in ordinary experimental work the engineer usually has to put up with, or is subject to, instrumental errors in other directions. Also the engineer generally has to work on plant of comparatively large dimensions and it is often a difficult matter to measure true average temperatures, quite independent of possible thermometer errors, as, for example, in measuring the temperature of flue gases in a large flue Notwithstanding such limitations, however, occasions arise when temperature measurements of a high degree of accuracy are essential.

Thermometer errors may be divided into two classes: (1) Personal errors of observation, and (2) Instrumental errors. With regard to errors of observation, when a reading is taken care should be exercised to avoid parallax, that is, the line of sight should be perpendicular to the stem of the thermometer, and the reading observed should be that at the centre of the tube. Careful watch should also be kept to see that no part of the thread of mercury has become detached from the main column Any detached portion can generally be got back by jerking the thermometer while holding it in the vertical position, or if this is not successful, by heating the thermometer to a sufficiently high temperature so that the main column joins the detached portion. If it be found that the detached portion moves upwards before the main column reaches it and the two do not join properly, this generally indicates the presence of a gas bubble, and for accurate work the thermometer might be rejected as useless, even for ordinary work little confidence could be placed on its readings. For instance, in a particular case when using an ordinary mercury thermometer, the indications were suspected of being several degrees too high. On testing the thermometer at the boiling point the reading came out to be about 10° F. too

high and on careful inspection it was seen that a very small bubble was lodging at the mouth of the bulb. After cooling to below this point and re-testing, the thermometer was nearly correct.

With respect to instrumental errors, besides that just mentioned there is the possibility of errors due to—defects of the glass bulb, internal or external pressure, time lag, differences between mercury and hydrogen or thermodynamic scales, exposure of stem, and defects in the thermal contact with the body whose temperature is measured. It is well known that glass, when heated and allowed to cool to the original temperature, does not immediately quite return to its original volume. This effect may be observed in a mercury thermometer by placing it in melting ice and after it has attained a steady reading taking it out and subjecting it to the boiling point temperature for thirty minutes or so. Then immediately returning the thermometer to the ice it would be found that the reading with an ordinary thermometer was perhaps 0·5° F. lower than previously. In the course of days, or perhaps weeks, it would probably return to the original reading. This change of reading just referred to is sometimes called the "depression of zero," and it is found to increase the higher the temperature to which the thermometer has been subjected.

Great attention has been paid to the manufacture of glass suitable for thermometers. The Bureau International has devoted attention to the French *verre dur*, and the Reichsanstalt to certain Jena glasses; particularly those known as 16^{III} and 59^{III} have been examined in detail. The National Physical Laboratory also recommend for the bulb and stem of thermometers certain British makes of glass. The various glasses are usually identified by a coloured stripe or stripes in the glass. It is found that with these glasses the depression of zero can be allowed for by taking a reading in ice, that is, the freezing point, immediately after the higher temperature has been obtained. With this object in view the fundamental interval may be determined by taking the boiling point first and immediately after this the freezing point, intending the thermometer to be used in this manner. This procedure may be necessary when a high degree of accuracy is required; but

to take an ice reading in order to get the true freezing point immediately after an observation of a higher temperature becomes troublesome in practice, and with high temperatures there is some risk of breaking the thermometer. In ordinary practice, therefore, it is not usual to go through the above procedure in measuring temperatures by mercury thermometers.

After manufacture the glass bulb of a thermometer is also liable to a decrease of volume in course of time, particularly if heated frequently to high temperatures, and this might cause a serious rise of the zero and of other readings unless the thermometer was well made This effect, however, is almost eliminated by the best makers by subjecting the bulb to prolonged annealing after manufacture. Thorough annealing requires from four to ten days at about 840° F , followed by a period of slow cooling for from three to six days.* The total change of the ice point for this process of annealing is about 30° C. (54° F) for Jena 16^{III} glass, and from 20° C. to 30° C (36° F. to 54° F) for Jena 59^{III} glass. Hence the importance of thorough annealing and ageing of the glass bulb before filling it with the mercury For the best work the bulb would be laid aside for several months to age the glass, because it is found that slow changes of volume occur for a long period after annealing

Errors due to variation of internal pressure on account of the head of mercury may cause slight errors in very delicate thermometers, but are usually of no particular importance in ordinary thermometers. If the thermometer is calibrated in the vertical position and is used in an inclined or a horizontal position, a sensitive thermometer may show slight errors due to this difference of position which can easily be allowed for.

The influence on the volume of the bulb of variations of external pressure due to alterations of the pressure of the atmosphere is not of any importance except in very delicate thermometers In any case a thermometer bulb should not be subjected to a pressure much different from that during calibration, or if it is unavoidable then a correction, if necessary, should be adopted by noting the change of the mercury column due to the pressure on the bulb and making an allow-

* *Heat Treatment of High Temperature Mercurial Thermometers,* by Dickinson, U.S A. Bureau of Standards. Reprint No. 32.

ance accordingly. Errors due to the lag of a thermometer in taking up the temperature to which it is subjected may be of serious importance when a varying temperature is being measured. When necessary it may be allowed for approximately when the change of temperature is slow by plunging the thermometer into a region of constant temperature and noting the readings at definite intervals of time. In any case a mercury thermometer would not be able to record rapidly fluctuating temperatures, such as occur, for instance, at the working face of a steam engine or internal combustion engine cylinder.

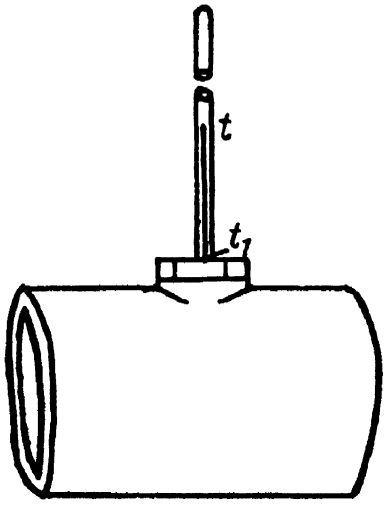


FIG. 4.—Stem of thermometer exposed.

Between the freezing and boiling points it is ordinarily intended that equal changes of volume of the mercury should signify equal changes of temperature. If the capillary tube forming the stem is of uniform bore this would correspond to equal divisions on the stem. Slight inequalities in the bore generally exist and this can be tested approximately by detaching a short portion of the thread of mercury and measuring its length at different positions. A convenient length of the thread can usually be detached by jerking the thermometer when up-ended. If the divisions on the scale are of equal length, which is usually the case, approximate corrections of the temperature for inequalities of the bore may be made in the manner just indicated. Owing to the fact that the relative expansion of mercury and glass does not take place at quite a uniform rate with changes of temperature as measured on the thermodynamic scale, for accurate work it may be necessary to compare a mercury thermometer with the hydrogen thermometer. With all the ordinary kinds of glass the divergence seems to be greatest in the neighbourhood of 40° C. (104° F.) and is of the order of $\frac{1}{10}$° C., say, about $\frac{1}{5}$° F., the mercury thermometer reading too high at the

intermediate points when correct at the freezing and boiling points.

It is the common practice to have the whole of the thread of mercury immersed when determining, or when testing, the freezing and boiling points. Under ordinary conditions of use, however, it is not generally possible to arrange the thermometer with the whole of the mercury immersed, and therefore some portion of the column of mercury would be at a temperature different from that in the bulb, leading to a definite error unless corrected. An approximate correction may be estimated if it is assumed that the emergent part of the column is not appreciably affected thermally by the immersed part Referring to the sketch in Fig 4, let t_1 be the reading on the stem at the beginning of the emergent part, t the temperature reading of the thermometer, and t_a* the temperature assumed for the emergent column. Let x be the required correction Then if v_0 is the volume of one degree division at zero temperature and m and g the coefficients of cubical expansion of mercury and glass respectively, the volume of the emergent column at temperature t_a is

$$v_0(t-t_1)(1+gt_a),$$

and if raised to the true temperature $(t+x)$ the new volume would be

$$v_0(t+x-t_1)\{1+g(t+x)\},$$

or approximately, since g and x are comparatively small,

$$v_0(t+x-t_1)(1+gt).$$

The new volume of the column if raised to $(t+x)$ would also be

$$v_0(t \quad t_1)(1+gt_a)\left\{\begin{matrix} 1+m(t+x) \\ 1+mt_a \end{matrix}\right\},$$

or again, since m and x are small, this could be written

$$v_0(t-t_1)(1+gt_a)\left(\frac{1+mt}{1+mt_a}\right)$$

$$\therefore \; v_0(t \quad t_1)(1+gt_a)\left(\frac{1+mt}{1+mt_a}\right) = v_0(t+x \; -t_1)(1+gt)$$

* An estimation of the temperature t_a may be obtained by employing a *Fadenthermometer*, i e a thermometer with an elongated bulb placed close to the emergent column It is the common practice, however, to take t_a to be the surrounding temperature measured at a distance of say three or four inches from the thermometer.

or, $$x=\frac{(m-g)}{(1+gt)(1+mt_a)}(t-t_1)(t-t_a) \quad . \quad . \quad (1)$$

or, since m and g are very small compared with unity,

$$x=(m-g)(t-t_1)(t-t_a) \text{ approximately} \quad . \quad (2)$$

Example :

$t=200°$ C. (392° F.) ; $t_a=15°$ C. (59° F.) ;
$t_1=35°$ C. (95° F.) ;
$m=0{\cdot}00018$ per ° C. ($0{\cdot}0001$ per ° F.) ;
$g=0{\cdot}000023$ per ° C. ($0{\cdot}0000128$ per ° F.).

Then, $x=(0{\cdot}00018-0{\cdot}000023)(200-35)(200-15)$
$=4{\cdot}8°$ C. (8·6° F. nearly).

Thus,

true temperature $=200+4{\cdot}8=204{\cdot}8°$ C. (400·6° F.).

A value commonly used for $(m-g)$ is $0{\cdot}00016$, but it varies slightly according to the class of glass used for the thermometer bulb.

Some distillation of the mercury may take place into the space over the mercury. With an emergent stem the vapour is liable to condense and to form small globules detached from the main column. These are sometimes not easy to get down to the main column, but if their length is noted an approximate correction can be made to the thermometer reading.

In using a mercury thermometer the ordinary practice is to insert it into a well or pocket to allow of easy withdrawal and to protect it when in use. The pocket should be made as thin-walled as possible consistent with a reasonable life, of brass or steel for ordinary purposes, and long enough to project right into the fluid. Theoretically the material of the pocket should be the same as that of the surrounding pipe or chamber, or have the same electro-potential to avoid electrolytic action, especially when the contacts are to be of long duration and the fluid is acidic. Monel metal, nickel and stainless steel are usually resistant to corrosion and chemical attack. Some particulars of suitable materials for use at fairly high temperatures are given in the table on p. 64. For a more extensive list of materials suitable for pockets or wells in contact with various chemical substances reference may be made to *The Instrument Manual*, (United Trade Press, Ltd.).

To improve the thermal contact between the thermometer bulb and the pocket a little non-volatile oil may be inserted in the pocket. Mercury is sometimes used for this purpose, but it may attack a brass pocket, and at high temperatures some distillation of the mercury may occur and the vapour could perhaps be dangerous to health in a closed position. In any case a few drops of mercury is usually sufficient with ordinary glass thermometers, for if too much is inserted the thermometer may float in the pocket.

A common arrangement of a thermometer pocket in a steam pipe is represented in Fig. 5. Unless the pipe is well insulated the metal of the pipe may be a few degrees below the average

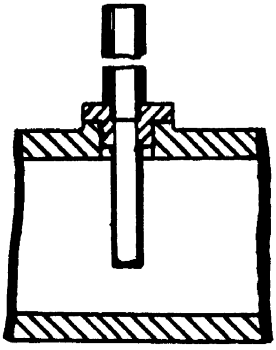


FIG 5 —Thermometer pocket with guard

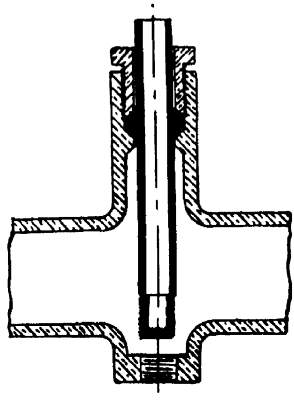


FIG 6 —Thermometer pocket insulated from pipe.

temperature of the steam and conduction of heat from the pocket to the pipe may cause a small error in the measured temperature of the steam. A better but more expensive arrangement is shown in Fig. 6, more especially for small bore pipes. The pocket is supported in a packed gland with insulation material between the pocket and the pipe and gland. The pocket has a screw thread on the outside near the bottom to improve the thermal contact between the fluid in the pipe and the pocket. This arrangement was used in the condenser experiments mentioned on p. 207.

For permanent installations thermometers are available with the bulb and stem in a metal case screwed for insertion into the pipe or pocket in the form shown in Fig. 7. Flue gas thermometers usually need special protection for insertion into

and for withdrawal from the flue, and may be obtained packed in a metal sheath. Alternatively, the sheath can be made from ordinary steel tubing with the ordinary flue gas thermometer packed in place by means of asbestos cord. The part of the steel tube opposite the thermometer scale would be cut away so that the reading can be made readily on withdrawal of the tube from the flue.

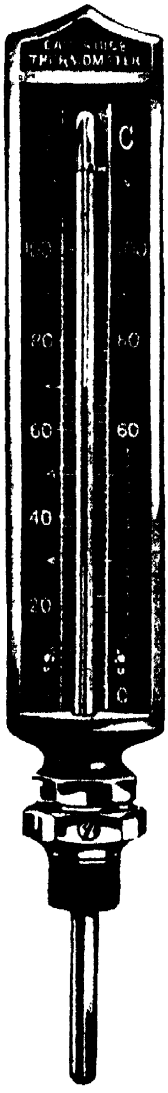


FIG 7.—Encased thermometer

When a single thermometer or pocket is inserted in a tube, pipe or passage through which a fluid is flowing after being heated or cooled the recorded temperature may not be a true average, especially if the velocity of the fluid is low, because of incomplete mixing of the fluid after leaving the heater or cooler. If the passage is large, as in an ordinary boiler flue, several thermometers may have to be used to obtain an average temperature. In small-bore pipes it may be desirable to provide a sudden reduction of cross-section at the thermometer, particularly if a right angle bend can be introduced before the thermometer is reached. Its effectiveness may be tested by lifting the thermometer to different positions in the pocket. If any appreciable changes in the readings are observable it may be necessary to introduce baffles in front of the pocket to mix the fluid. Another common source of error not always recognised sufficiently well by engineers arises if the walls of an enclosure containing a fluid whose temperature is being measured are not at the same temperature as the fluid. Thus, in measuring the temperature of flue gases, for instance, the thermometer, or the pocket or sheath if used should be screened from the radiations emanating from any colder or hotter surfaces, as from the boiler shell, tubes or walls. Otherwise the thermometer may read below or above the true temperature of the gases. This effect is further discussed on p. 57.

For general experimental work the bulb of a mercury

thermometer should not be larger in diameter than the stem, so that it can be easily inserted into close-fitting holes or pockets. It is also desirable to have the scale graduated so that the lowest reading commonly used is not less than about 3 in. above the bulb, so that observations of temperature may be made without having to raise the thermometer from the well or pocket. For laboratory work it is sometimes convenient to have special sets of thermometers for succeeding ranges of temperatures so that the degree divisions may be wider spaced than if one thermometer were used throughout a large range of temperature. For fairly accurate work the thermometer stem should be graduated in half degrees so that estimations of temperature could be made to say, 0·1° F. If the freezing and boiling points do not come on the scale of such special thermometers it is advisable to have them constructed with small enlargements in the stem so that a special mark can be made on the stem to indicate the freezing or boiling points.

In the best thermometers the graduations are engraved on the thick stem with a layer of white enamel behind the capillary tube to facilitate observations. If the bore of the tube is very fine then readings may be facilitated by the use of a lens-front stem. Thermometers constructed with scales of porcelain or of paper attached to the thermometer stem inside a thin glass covering tube may be liable to a displacement of the scale unless well constructed, and the thermometer is more fragile than when the scale is engraved on a thick glass stem. This form of construction, however, may allow the thermometer to float in ordinary liquids, and the natural circulation of the air enclosed in the space in the glass cover reduces the error due to the emergent stem.

The National Physical Laboratory at Teddington, and the U.S.A. Bureau of Standards at Washington, for a fee will test a *suitable* thermometer and supply a certificate of corrections. The National Physical Laboratory has developed certain rules and limits of accuracy governing the tests made by them on thermometers and these are given in detail in the issue " Tests and Measurements undertaken by the Physics Department, Heat Division."

When a fairly large number of ordinary mercury thermo-

meters are used such a course might be too expensive for every thermometer to be certified. One or more standard thermometers could be tested and certified and kept for calibrating the ordinary thermometers in use. The thermometer to be calibrated and the standard one might be inserted together into a small but fairly deep bath of water, oil, or a melted salt, provided with a good stirrer and carefully shielded from draughts. The bath would be heated gently and the comparisons made with slowly rising temperatures, keeping the liquid well stirred. Comparisons with falling temperatures are generally unreliable because the mercury column is liable to stick. Usually the standard thermometer should have the column of mercury fully immersed so as to avoid stem corrections. Whether the thermometer to be calibrated would also have its stem fully immersed would depend upon the circumstances of its use. If calibrated fully immersed and then used with the stem emergent, a stem correction may have to be made. It is generally advisable to recalibrate ordinary thermometers periodically as they are liable to slight alterations in their readings in course of time.

The British Standard Specification No. 593 : 1940 for General Purpose Laboratory Thermometers gives recommended particulars for different ranges, classed as a series A to E. Series A thermometers are intended for accurate work covering ranges of about 30° C. or about 60° F. with the scales divided to 0·1° C. or 0·2° F., having the zeros marked on the stems, while series D are for less accurate work with the complete scale marked from 0° C. or 32° F. up to their maximum temperatures and divided in a manner suited for each range. Recommendations are also made in respect of suitable inscriptions on the thermometer stems ; and a list is given of the thermometric glasses approved by the National Physical Laboratory.

It will be realised that some difficulty is experienced with ordinary mercury thermometers to ensure an accuracy of measurement within $\pm 0{\cdot}1°$ F., even over the range from freezing to boiling points. Physicists and chemists in the laboratory sometimes work to a much higher degree of accuracy than this by using sensitive and carefully graduated thermometers, and by taking some of the special precautions which have been described.

In many cases with which the engineer is concerned, however, it is the accurate measurement of a difference of temperature that is of primary importance, as for instance, the increase in the temperature of circulating water flowing through a condenser. If the rise of temperature is not more than, say, 30° or 40° F., and no standardised thermometer is available for comparison, it is often sufficiently accurate to use two similar thermometers and to compare their readings in a liquid bath, as described on p. 22, over the range of temperature required, for it is found that, even if the thermometers do not read alike, there is commonly a practically constant error of one relatively to the other, and that either of them would indicate the rise of temperature fairly accurately were it practicable to use one thermometer at both the inlet and the outlet. A check can sometimes be obtained by interchanging the two thermometers occasionally during an experiment if the temperatures are quite steady, and then noting the readings.

When a small rise of temperature needs to be measured accurately, as in calorimeters or similar apparatus, special thermometers are used either of the Beckmann type, or one having a solid stem with the tube of relatively large bore, with the scale restricted to a narrow range of about 6° C., giving one degree a length of about 5 cm. divided into hundredths of a degree. With the use of a magnifying glass estimates may be made to perhaps 0·002°. At the top of the stem a small chamber is provided into which some of the mercury in the tube may be discharged on heating the thermometer. The mercury in the chamber can be returned to the tube by heating the thermometer sufficiently to cause the mercury to reach the chamber and then allowing it to cool with the thermometer inverted. In this way the zero reading can be adjusted to bring the readings on the scale at different temperatures. The value of the scale divisions alters according to the amount of mercury in the bulb and stem, and the calibration of the thermometer should take into account these variations in the scale values. The British Standard Specification No. 791 : 1938 gives particulars of standard constructions of bomb calorimeter thermometers and of the thermometric glasses approved by the National Physical Laboratory.

Liquids such as alcohol of freezing point −111·8° C., toluene, or pentane in glass are available for low temperatures below the freezing point of mercury (−38·87° C.). Pentane may be used for temperatures down to −200° C. (−328° F.). One objection to the use of volatile liquids such as these in thermometers is their liability to distil into the stem and to condense there if the stem happens to be colder than the bulb. When a spirit thermometer is inserted into a low temperature region the receding liquid wets the wall of the tube and it may be necessary to wait a little before taking the reading to allow time for the liquid on the tube wall to drain down.

Meteorological thermometers giving maximum and minimum temperatures attained during an interval of time are available in different forms. In one common type of mercury maximum thermometer the nearly horizontal thermometer has a small iron index in the tube. With rising temperatures the index is pushed forward by the surface of the mercury column and is left in position when the mercury recedes. The index can be brought back for the next observation of the maximum temperature by using an ordinary steel magnet. In another construction recommended in the British Standards Specification No. 692 there is a constriction or plug placed in the bore below the lowest graduation mark so that when the temperature falls the mercury column is not drawn back past the constriction. The mercury column is induced to join that in the bulb by a shake of the thermometer while held vertically. The above specification also gives a list of thermometric glasses approved by the National Physical Laboratory.

The expansion liquid in the minimum thermometer is usually pure ethyl-alcohol. The above B.S. specification recommends an index of black glass about 0·8 in. long to be placed in the tube. When the temperature falls the capillary surface of the column drags the index with it and leaves the index in position as the temperature again rises. A shake of the thermometer returns the index to a higher position.

Six's self-registering thermometer was designed to combine the maximum and minimum reading thermometers. It consists of one continuous tube usually bent to U form, where the two end parts contain alcohol or similar spirit, and the intermediate part of the tube is filled with mercury. The

right-hand part of the tube is of relatively large diameter and the expansion or contraction of the spirit in this part dominates the movement of the intermediate column of mercury. When the temperature rises the surface of the mercury in the left leg pushes a spring-loaded index along the graduated tube in the manner previously described, and when the temperature falls the index is left in the maximum temperature position in the tube. In the same manner, as the temperature falls the other end of the mercury column in the right-hand leg pushes a similar index up the tube, leaving it in place on the next rise of temperature, thus registering the minimum temperature.

Clinical maximum temperature thermometers usually have a constriction below the lowest graduation so that the column of mercury stands in position as the temperature falls and is therefore easily read. The column rejoins the mercury in the bulb on shaking the thermometer when held vertically. A special mark is provided at the normal blood temperature 98·4° F. The British Standard Specification No. 691 gives particulars of the recommended construction of clinical thermometers, including the thermometric glasses approved by the National Physical Laboratory.

In the course of the manufacture of ordinary mercury thermometers the tube is sealed off with the bulb and stem heated and full of mercury. On cooling the mercury contracts and leaves almost a perfect vacuum over the column of mercury when atmospheric temperature is attained. A reference to the accompanying table of the vapour pressure of mercury shows that the internal vapour pressure does not introduce any serious variations of internal pressure in the thermometer until fairly high temperatures are attained.

TENSION OF MERCURY VAPOUR

Temperature	° C.	50	140	220	300	360
	° F.	122	284	428	572	680
Absolute pressure, mm. mercury .		0·015	1·76	31 96	246·7	785·1

In the case of mercury thermometers intended for the measurement of high temperatures, say, from about 600° F. to about 900° F., it is usual to construct them with an inert gas such as nitrogen, introduced under a suitable pressure in the upper part of the thermometer before the stem is sealed

off. This pressure not only prevents an excessive vaporisation of the mercury and thus reduces the liability of condensation in the upper part of the stem, but may maintain a more uniform pressure inside the thermometer. Should a bubble of the gas get entangled in the mercury in the stem, a separation of the column of mercury might introduce a serious error in the readings unless noticed immediately, and it is sometimes difficult to get rid of the bubble.

With a thermometer deeply immersed and fixed in position it is not always possible to see whether or not the column of mercury is complete, but by careful observation an experimenter can usually judge from the readings obtained, as small variations of temperature during the course of an experiment may be expected, and generally there is more than one thermometer to be observed. If the mercury column is broken the top of the column may stick for some time at the maximum temperature recorded ; but whether it ought to record a steady temperature or not can be judged by the readings of the other thermometers, that is, a variation of temperature at one point of an experimental apparatus is usually reflected by similar consequent changes of temperature at other points.

The character of the glass forming the thermometer bulb also limits the temperatures measurable by mercury thermometers. Jena 59^{III} borosilicate glass cannot be used safely above about 500° C. (932° F.), and for Jena 16^{III} the limit is about 450° C. (842° F.). Under the internal pressure the bulb is liable to a permanent increase of volume above these temperatures.

Specially mounted mercury thermometers are available to measure the temperatures of salt, lead or tinning baths, varnish, gum melting and oil boiling pans, etc. The glass thermometer is usually enclosed in a metal tube with a glass-fronted scale, with copper dust packing round the thermometer bulb to give good thermal contact. The British Standards Specification No. 619 gives recommendations for laboratory incubator, water bath and oven thermometers, and No. 695 for dairy thermometers.

The usefulness of mercury or liquid-in-glass thermometers in industry is limited by their fragility unless they are well protected, and by the difficulty of taking readings in dark or

out-of-the-way places since it is practically impossible to make them readable at a distance. These drawbacks have been overcome to some extent by the development of mercury-in-steel dial or indicator thermometers for readings up to about 550° C. (1022° F.). The system is represented in outline in Fig. 8. The steel bulb, capillary connecting tube, and Bourdon gauge tube are completely filled with mercury. An increase in the temperature of the mercury in the bulb causes the

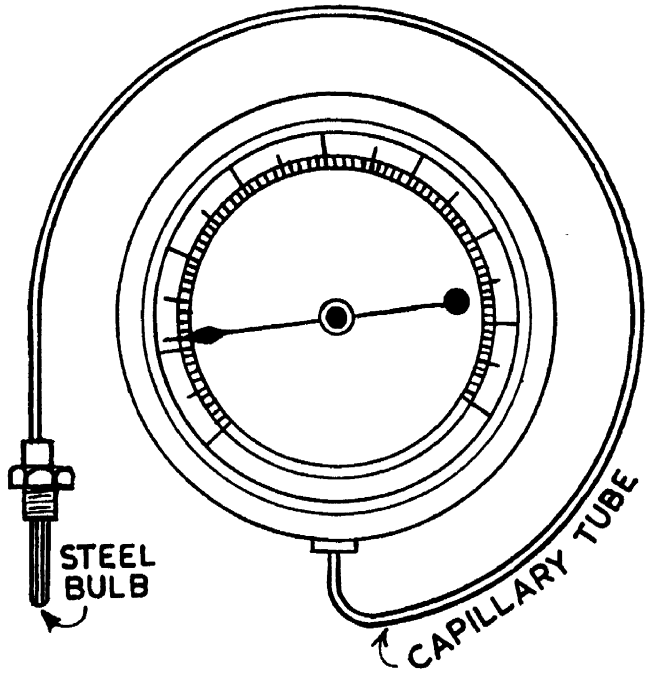


FIG 8.—Index or dial type of thermometer.

mercury to expand and dilate the Bourdon tube which then moves the pointer over the scale as in an ordinary pressure gauge, but having the scale graduated in degrees of temperature with practically uniform spacing. In this case the Bourdon tube can be made of robust construction so that with falling temperatures the elastic forces provided by the tube enable it to follow up the contraction of the mercury in the bulb and overcome the friction of the gauge mechanism and of the mercury moving in the capillary tube. With suitable precautions the length of the capillary tube may be as much as 200 ft. If the difference of level between the bulb

and the dial is not the same as that during the calibration a correction in the zero reading may be necessary to allow for the difference of head.

Changes of barometric pressure should make little difference to the readings of temperature whether due to day-to-day variations or to elevation above sea level because the volume of the steel bulb and the other parts cannot be altered appreciably by alterations in the atmospheric pressure. Changes of elasticity of the Bourdon tube due to ordinary changes in the temperature of this tube should not of itself affect the accuracy of the reading as the tube merely follows the changes in volume ; but the differential expansion of the mercury and the Bourdon tube with a change in the dial temperature may have a small effect on the zero reading and therefore affect all the readings by the same amount. Another possible source of error is that due to the differential expansion of the mercury in the capillary tube when the temperature of this tube is appreciably different from that at the time of the calibration. This error is usually reduced to negligible proportions by using a capillary tube of fine bore, and when the tube is very long or a higher degree of accuracy is required, either by a suitable selection of the material of the tube, or by providing at intervals compensating volumes made of a suitable metal to accommodate the estimated relative change in volume of the mercury in the adjacent capillary tube. In well-designed instruments of this type the error should not exceed $\pm 0{\cdot}5$ to $\pm 1\%$ of the maximum temperature up to about 550° C. Other liquids such as xylene up to about 400° C., or alcohol up to 150° C., are sometimes used instead of mercury, especially where the risk of contamination would be serious if mercury should leak from the bulb. In such case the mercury bulb might be inserted into a suitable pocket even though the lag of the instrument is thereby increased.

The bulb is usually made of special steel alloy. Where there may be a liability to corrosive action, the bulb and capillary tubing can be covered with lead, copper or tin. Stainless steel or nickel-plated bulbs may be supplied where necessary. When the bulb has to be withdrawn frequently specially flexible capillary tubing at the bulb end is an advantage.

Vapour pressure and gas pressure thermometers having the

same general form as the mercury-in-steel thermometer are also available. In the vapour pressure thermometers a volatile liquid partly fills the metal bulb connected by a length of capillary tube to a pressure gauge, usually of the Bourdon tube type, with the scale graduated in degrees of temperature. The bulb should be more than half-filled with the liquid, and the capillary tube should project well into the bulb so that the tube could remain filled with liquid even if the bulb were placed in a horizontal position. If the capillary and the Bourdon tubes have temperatures below that of the bulb the vapour pressure is transmitted to the gauge by the liquid; but, if the temperatures of these tubes were higher than that of the bulb the tubes would be more or less filled with superheated vapour.

The measurable range of temperature is dependent to some extent upon the critical temperature and pressure of the liquid for the higher limit, and on the low vapour pressure for the lower limit. For example, with water as the liquid, the critical temperature is near 374° C. (705° F.) and the pressure about 218 atmospheres. Thus in practice the higher limit of the temperature must be well below the critical value or the Bourdon tube may need to be so strong as to be far too stiff to record effectively when the vapour is near to atmospheric pressures. With water as the working liquid the lower limit of temperature should be above 100° C. or variations in the atmospheric pressure may cause appreciable errors at or below 100° C. In this case the practical range may be 120° C. (248° F.) to 220° C. (428° F.), corresponding to vapour pressures of 28·8 to 336 lb. per sq. in. abs., with change of pressure varying from 0·5 to 3·6 lb. per sq. in. per deg. Fahr. The scale of temperature with the ordinary gauge mechanism therefore widens out as the temperature rises. With ethyl-alcohol the practical range on this vapour pressure system may be 90° C. to 170° C. (194° F. to 338° F.), and with toluene 150° C. to 250° C. (302° F. to 482° F.). For lower temperatures the more volatile liquids such as are used in coolers or refrigerators are required. The general appearance of a dial thermometer on this system is shown in Fig. 9 as made by The British Thermostat Co., Ltd., of Sunbury-on-Thames, Middlesex, and it illustrates the variable character of the scale divisions. A

list of suitable liquids with the relevant physical properties is given in the British Standard Code 1041 : 1943, on " Temperature Measurement."

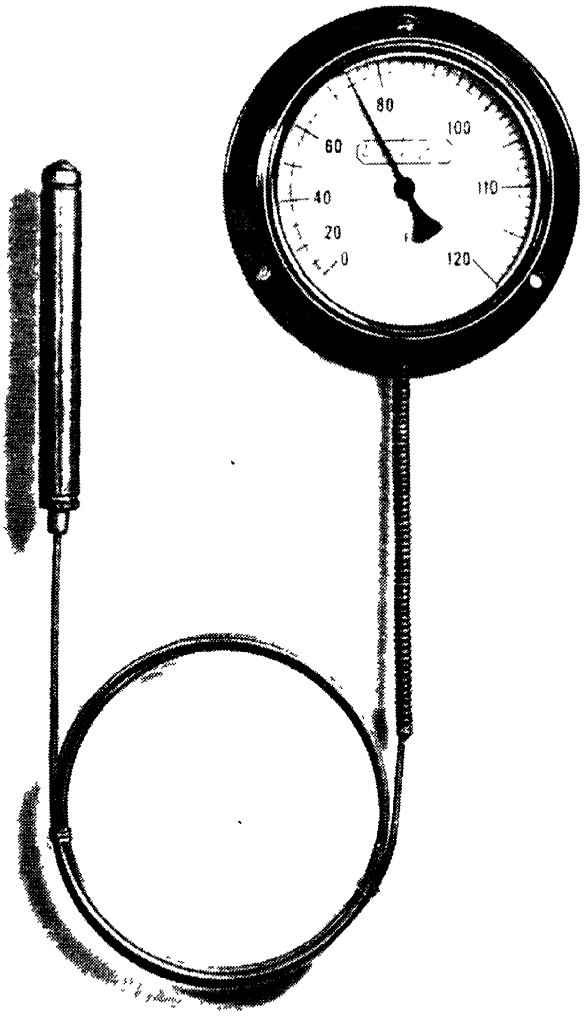


FIG. 9 —Vapour pressure dial thermometer (Courtesy The British Thermostat Co Ltd)

The coefficient of elasticity of the Bourdon tube may be affected by changes in the temperature of the tube and may cause appreciable errors when this temperature is much different from that during calibration unless compensated for by the

introduction of a suitable bimetallic link in the mechanism. Otherwise the ordinary variations of the temperature of the gauge and of the capillary tube have but little effect on the accuracy. When the bulb is at a higher level than the gauge, and is also at a higher temperature, the head of liquid in the connecting tube should be allowed for in fixing the pointer. It is fairly evident that this system may not operate satisfactorily when the temperature of the bulb is sometimes above and sometimes below that of the capillary tube and gauge, for then the connections may change from a filling of liquid to that of superheated vapour and vice versa. Under these conditions the response of the instrument to changing temperatures of the bulb may appear to be sluggish.

The basis of the constant volume gas thermometer was discussed on p. 6 in reference to the standard scale of temperature. The same principle is used in the constant volume gas expansion dial type of thermometer used in industry, though for practical reasons it does not have the same degree of accuracy as the gas thermometer. In these instruments the changes of pressure of a nearly constant volume of an inert gas in a metal bulb are transmitted through a small-bore capillary tube to a pressure gauge usually of the Bourdon type, graduated in terms of temperature as a uniform scale. It may be arranged to suit various ranges of temperature from well below the freezing point to over 1000° F. If the capillary tube and the gauge are subject to temperatures much different from that existing during calibration errors may be caused dependent upon the proportion of the connecting volume to the volume of the bulb, and on the change of the coefficient of elasticity of the Bourdon tube. While the day-to-day variations of the barometric pressure may not cause serious errors those due to altitude above sea level may be more serious unless the instrument was calibrated for the altitude conditions, or the pointer made so as to be capable of adjustment to allow for the altitude.

In the testing of dial thermometers readings should be observed at a series of decreasing temperatures as well as with increasing temperatures to have an estimate of the magnitude of the possible hysteresis errors.

Instead of the pointer moving over a temperature scale

the recorder arrangement with an inking pen moving over a circular chart may be adopted, as represented on p. 132. The gauge may be used to operate a temperature controller or regulator as described on p. 131.

The dilatation or expansion of a suitable metal may be used to indicate or to measure changes of temperature. The lengthwise expansion of a metal rod of reasonable length is usually too small to give a direct indication of temperature and needs to be magnified considerably to be made readable on an indicator. The number of metals available is also limited because of physical changes under prolonged and repeated heating causing undesirable changes in the coefficient of expansion. More usually the metal is formed into a bimetallic strip by welding or hot-rolling two metal strips together having different coefficients of expansion, such as invar and brass for use up to about 300° C., or two different alloys of nickel and iron for temperatures up to about 550° C. The different expansions of the two metals causes the bimetallic strip to change in curvature with change of temperature, and if the strip is in the form of a helix the change of curvature causes a relative rotation of the two ends about the axis of the helix. The British Rototherm Co., Ltd., of London make use of this arrangement to produce a robust form of dial thermometer. The bimetallic strip is wound into several helices arranged co-axially one within the other. This enables the required length of strip to be accommodated in a stem length of a few inches. It is enclosed in a protective sheath of stainless iron to which one end of the strip is attached while the other end is fixed to a spindle having a pointer moving over the circular scale of temperature. The helices are so compensated that any tendency to the lateral displacement of the spindle due to one helix is automatically counteracted by an opposite tendency of one or other of the other helices. The spindle is fully floating and retains its position relative to the scale without using bearings. Friction is thus practically eliminated, while the arrangement is robust enough to withstand damage by ordinary mechanical shocks. The standard sheaths or stems are $\frac{5}{16}$ in. and $\frac{5}{8}$ in. diameter and the dials are 7, $4\frac{1}{2}$ and $2\frac{1}{2}$ in. diameter. Several standard ranges of temperature are available, with special designs for

ranges up to about 1000° F. The apparatus can also be arranged to control temperatures as described on p. 131.

The Rheostatic Co., Ltd., of Slough, Bucks., make a compact thermometer of the bimetallic type for particular application to heating and hot water systems for temperatures up to 212° F. The sensitive stem of the thermometer is a bimetallic scroll to whose free end the indicating disc is secured so that the change of temperature causes the rotation of this disc against an inscribed scale at the thermometer head. This thermometer is provided with a bronze pocket $\frac{9}{16}$ in. diameter and screwed $\frac{1}{2}$ in. B.S.P. It can be mounted across a $1\frac{1}{2}$ in. diameter pipe in a standard Tee, or at the bend of a 1 in. diameter pipe in a standard reducing pitcher Tee.

Sulphur Boiling Point.—This boiling point has been determined with great accuracy and is generally suitable for purposes of calibration. It is also used for the determination of δ in the Callendar equation (4) on p. 39. If this temperature were not obtained with a high degree of accuracy an appreciable error might be involved in the measurement of high temperatures by means of platinum resistance thermometers when use is made of the equation or similar equations.

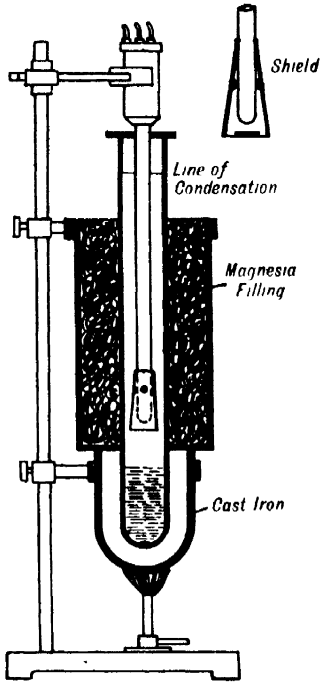


FIG 10.—Sulphur boiling point apparatus.

One convenient arrangement of the sulphur boiling point apparatus is shown in Fig. 10. A hard glass tube containing a suitable amount of sulphur is first passed through the hole at the bottom of the sheet metal cylinder, which is then packed with magnesia or similar insulating material. The thermometer is inserted into the tube and well clear from the surface of the sulphur. In order to shield the bulb or resistor of the thermometer from radiations, and to prevent drops of condensed liquid sulphur from running down the stem on to

the bulb, it is necessary to use a screen or shield of sheet aluminium, illustrated in the side sketch. If the shield were omitted the reading of the thermometer might be a degree or so too low. The end of the glass tube could be heated by means of a gas burner acting on a cast-iron cover or shield to give a fairly uniform supply of heat. By careful regulation of the gas it is not difficult to keep the sulphur boiling so that little or none of the sulphur vapour leaks to the atmosphere, and gives a line of demarcation on the tube above which is seen crystals of sulphur and below condensed vapour running down in the tube. To obtain the highest degree of accuracy the recommendations of the International Temperature Scale of 1948 (see p. 248) should be followed.

In perhaps its simplest form an ordinary steel tube of about 2 in. bore with a tightly screwed cap may be used for occasional calibration tests at the sulphur boiling point, with the tube insulated by means of thick asbestos rope. Two ordinary Bunsen burners may be required to heat this apparatus in a reasonable time, but careful control of the heating may be necessary as the boiling point is reached to avoid the escape of sulphur vapour into the atmosphere.

It is sometimes necessary to calibrate a thermometer or pyrometer at higher temperatures than the boiling point of sulphur and recourse is then usually had to the freezing or the melting point of suitable metals or salts of definite composition. Such methods are well adapted to the calibration or standardisation of thermojunctions, by immersion in the melted metal or salt in a crucible. Readings of the e.m.f. would be obtained as cooling took place, and the point of freezing is generally recognised by the metal remaining at nearly constant temperature for a few minutes during the process of solidification. The melting or freezing points of silver and copper should be obtained in a reducing atmosphere, which may be obtained by using a graphite crucible and covering the metal with powdered graphite and a graphite crucible lid. If these metals are exposed to the atmosphere when melted they readily oxidise and this lowers the melting point appreciably.

The crucible containing the metal should be deep enough to give sufficient immersion of the pyrometer under test.

Some metals may have a tendency to under-cool, that is, to remain liquid at temperatures a few degrees below the actual freezing point, but on solidification the temperature rises to practically the same point as when under-cooling is absent. Under-cooling may be almost eliminated in most cases by frequent stirring by means of the pyrometer itself. The under-cooling effect is usually more marked the higher the temperature to which the metal is raised above its freezing point, and the more rapid the rate of cooling. Special electrical furnaces have been designed for the melting of metals at high temperatures and are usually capable of close regulation. In the interest of the highest degrees of accuracy obtainable from the melting or freezing points of metals reference should again be made to the International Temperature Scale of 1948.

In subsequent chapters the other important methods of measuring temperature will be described and discussed. Thermometers intended to measure temperatures higher than those commonly measurable by means of ordinary mercury thermometers may be termed " pyrometers."

CHAPTER III

ELECTRICAL THERMOMETERS AND PYROMETERS

Electrical Resistance Thermometers.—The electrical resistance of a pure metal increases with an increase of temperature. This property may be used to measure temperatures provided the relation between the resistance and the temperature is known and remains invariable. The choice of metals for this purpose is very restricted because of the difficulty of preserving an invariable relation between the resistance and the temperature in any particular specimen of wire, and for high temperatures is further limited to the platinum series. Sir William Siemens * first proposed the platinum resistance thermometer and employed it principally in metallurgical operations, but it was abandoned because in this case the resistance of the platinum wire was found to alter seriously after prolonged or repeated exposure to high temperatures. The Siemens' pyrometer consisted of platinum wire wound on a cylinder of fireclay, with platinum leads to the thermometer head. These were surrounded by an iron sheath to protect the wire from the action of outside gases at high temperatures.

The permanent alteration of the resistance of platinum wire under such conditions was examined by a committee of the British Association,† and it was discovered that when the platinum wire was surrounded by a platinum sheath no serious permanent change of resistance occurred due to high temperatures. It was found that a permanent change took place if the platinum wire coil were enclosed in an iron sheath and subjected to high temperatures, due to the reducing action of the gases produced by the iron sheath causing the platinum to combine to some extent with reduced silicon taken from the fireclay cylinder.

Professors Callendar and Griffiths ‡ experimented with the

* *Phil. Mag.*, Vol. XLII, 1871. † *Brit. Assoc. Report*, 1874.
‡ *Phil. Trans. Royal Soc.*, Vol. CLXXVII, 1888. *Phil. Mag.*, February, 1899.

platinum resistance thermometer and after careful investigation came to the conclusion that pure platinum, when not subjected to strain and when carefully handled, always possesses the same resistance at the same temperature.

In this relation it may be remarked that the resistance of a wire increases slightly when subjected to tensional strain. This property is made use of in electrical resistance wire strain gauges,* and the ratio of the proportionate change of resistance to the mechanical strain is usually termed the "strain sensitivity." It is found to be different from, and usually greater than, that calculated from the change in the dimensions of the wire subject to the strain. The difference is generally ascribed to a change in the specific resistance of the metal when under strain. From these considerations it would follow that the wire in the resistance thermometer should be supported as free as possible from variable mechanical strain.

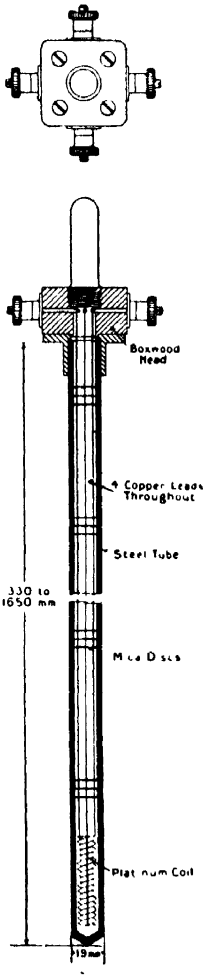


FIG. 11.—Platinum resistance thermometer (laboratory type).

One arrangement of the laboratory type of resistance thermometer is shown in Fig. 11 as constructed by the Cambridge Instrument Co., Ltd. The fine platinum wire, about 0·008 in. diameter, is wound on a mica frame made of two strips of mica fixed so as to form a + in section. The wire touches the bottom of the serrated edges of the mica strips and is thus maintained practically free from mechanical strain. The four leads to the head of the thermometer may be of copper or silver if it is to be used only for moderate temperatures, or of platinum for high temperatures, and these leads are insulated by mica washers which also prevent convection currents of air in the tube. In place of the platinum

* "Electrical Resistance Wire Strain Gauges," by F. Aughtie, Ph.D., M.Sc., *Proc. Inst. Mech. Engrs.*, 1945, Vol. 152, No. 2, p. 213.

wire coil some makers prefer to use platinum strip as it responds more readily to changes of temperature.

The protecting sheath should seal the thermometer to prevent the condensation of moisture on the frame and wires when measuring low temperatures. A slight film of moisture between the turns of wire may lower the apparent resistance of the thermometer. The sheath may be of glass, steel, quartz or silica, or porcelain according to the highest temperature to be measured. A glass sheath may serve up to about 300° C. (572° F.); an iron or steel sheath up to about 700° C. (1292° F.), and a silica or glazed porcelain sheath up to about 1200° C. (2192° F.) if the leads to the thermometer head are of platinum. The sheath should be impervious to furnace or other gases at high temperatures to avoid possible contamination of the platinum.

FIG. 12.—Platinum resistance thermometer (commercial type).

From his experiments the late Professor Callendar showed that mica has no chemical action on platinum, but it has the disadvantage that it tends to crumble when subjected to temperatures above 900° C. (1652° F.) for lengthy periods. It is found, however, that 1000° C. (1832° F.) is about the useful limit of a coil of pure platinum wire with platinum leads, for when subjected to higher temperatures the platinum is sometimes liable to permanent changes of resistance, though occasional temperatures may be observed for short periods as high as 1200° C. (2192° F.) without subjecting the instrument with platinum leads to serious damage. Professor Callendar also found that all joints in the thermometer itself should be made by fusion because metallic solderings are volatile at high temperatures and may contaminate the platinum.

Fig. 12 gives an outside view of the commercial pattern of the resistance thermometer as built by the Cambridge Instrument Co. Ltd. It is provided with an inner sheath of refractory material and an outer steel tube for protection against the accidental breakage of the inner sheath. The outer tube would be removed for high temperatures. The sheaths or tubes should be as light as possible consistent

with sufficient strength to avoid errors arising from excessive conduction of heat from the heated portion. The electrical connections at the head of the thermometer are completely enclosed to prevent contamination by dirt, fumes or moisture under industrial conditions.

Professor Callendar suggested the following notation and terms for convenient use in platinum resistance thermometry and these are now generally adopted.

The Fundamental Interval is the increase of resistance $(R_{100}-R_0)$ between 0° C. and 100° C.

The Fundamental Coefficient is the average increase of resistance per deg. Cent. between 0° C. and 100° C. divided by the resistance at 0° C., thus,

$$\frac{R_{100}-R_0}{100R_0}=\frac{1}{100}\left(\frac{R_{100}}{R_0}-1\right) \quad . \quad . \quad . \quad (1)$$

The Fundamental Zero is the reciprocal of the fundamental coefficient with minus sign, thus,

$$-\frac{100R_0}{R_{100}-R_0} \quad . \quad . \quad . \quad . \quad (2)$$

and this represents the temperature on the platinum scale of the thermometer at which its resistance would be zero.

$$\text{Platinum Temperature}=p_t=\frac{R_t-R_0}{R_{100}-R_0}\times 100 \quad . \quad (3)$$

The Difference Formula expresses the relation between the temperatures on the gas scale t° C. and on the platinum scale p_t.

$$t-p_t=\delta\left\{\left(\frac{t}{100}\right)^2-\frac{t}{100}\right\} \quad . \quad . \quad . \quad (4)$$

The value of the constant δ depends principally upon the purity of the platinum wire and it should be noted that the above expression vanishes when $t=0$° C. and 100° C. Therefore δ may be determined by an observation at some known temperature, usually the boiling point of sulphur, 444·6° C. (832·3° F.) at the standard atmospheric pressure. Professor Callendar determined the boiling point of sulphur on the gas scale with great accuracy. This was necessary because a small error at this temperature introduced an appreciable error in

the difference formula at, say 1000° C., unless tests were applied at temperatures above 444·6° C.

Comparisons made by various experimenters between the gas and the platinum thermometers have shown that the difference formula 4 holds up to the practical limit of the platinum thermometer when using pure platinum ($\delta=1{\cdot}5$). At temperatures below −40° C., however, the formula gives too low a reading, amounting to about 2·3° C. at −190° C.

It does not strictly hold, however, for impure platinum when calibrated by the Callendar method, viz. the freezing and boiling points of water and the boiling point of sulphur. The following table exhibits corrections at various temperatures for δ varying from 1·525 to 1·90.

Temp. ° C.	Correction in ° C. for values of δ.						
	1·525.	1·550	1·575.	1·600.	1·700.	1 800.	1 900.
200	+0·02	+0·05	+0·08	+0·10	+ 0·16	+ 0·20	+ 0·21
600	−0·09	−0·18	−0·30	−0·40	− 0·88	− 1·42	− 1·96
1000	−3·3	−5·2	−6·8	−8·2	−13·1	−17·1	−20·8

If thermometers of impure platinum wire are calibrated at a fourth temperature, say, the freezing point of silver, and the difference coefficient δ of the Callendar formula (4) is written $\delta=a+bt$, then this scale is very nearly in agreement with that of a thermometer of pure platinum.*

It is sometimes specified that for accurate work the value of δ in the platinum thermometer coil or resistor should not be greater than 1·52, and that the wire should be free from mechanical strain and thoroughly annealed before use.

Another way of expressing the above relationships is to combine the equations 3 and 4 into the form given in the International Temperature Scale of 1948 quoted on p. 243, where

$$R_t=R_0(1+At+Bt^2) \quad . \quad . \quad . \quad (5)$$

A and B are constants derivable from the values of R_t obtained

* *Platinum Resistance Thermometry at High Temperatures*, Waidner and Burgess, U.S.A. Bureau of Standards. Reprint No. 124.

at the boiling points of water and sulphur at the standard atmospheric pressure, after R_0 has been measured at the ice point, 0° C. The above expression (5) is also modified to satisfy temperature conditions below the ice point down to the boiling point of oxygen. Reference is also made on p. 244 to the desired purity and physical condition of the platinum of which the thermometer should be made. The extension or

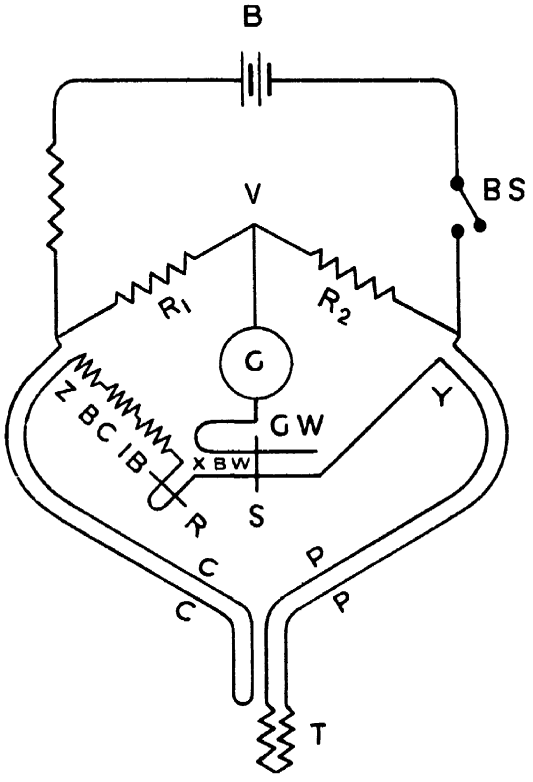


FIG 13.—Arrangement of Wheatstone Bridge and Callendar four-lead compensation.

extrapolation of the above expression (5) to high temperatures with impure platinum would lead to errors similar to those given in the preceding table.

If the platinum wire is frequently subjected to high temperatures for prolonged periods, the crystalline structure may be affected, especially if the wire is strained by vibrations or by relative expansion on its supports, and may result in changes in the values of R_0, A and B and in the equivalent

value of δ in eqn. 4. The use of the resistance thermometer in industry is therefore usually limited to moderate temperatures, say to about 600° C (1112° F.) as the higher limit with continuous heating.

The resistance of the platinum coil is usually measured by some form of Wheatstone bridge. The arrangement shown diagrammatically in Fig. 13 is due to Professor Callendar. The ratio coils R_1 and R_2 having negligible temperature-resistance coefficients are adjusted to equality and arranged to be approximately the mean resistance of the platinum coil T. The coil T and the leads P are placed on one side of the bridge as indicated and are balanced by the compensating leads C, the resistance coils Z, BC, IB, and the rheostat R and bridge wire BW. The leads C and P are alike and are grouped in one cable and thus all acquire practically the same temperature at any point along the length. Therefore any change of resistance of the leads P is automatically compensated by an equal change in C. The rheostat R is used to adjust the resistance on that side to the zero conditions, and the ice-bobbin IB is a standard-testing resistance to balance that of each thermometer coil T to the standard value when the coil is immersed in ice. To obtain a balance between V and S the slider S is moved along the wires GW and BW until the galvanometer needle G shows no deflection when the tapping key BS makes contact. The accuracy of this arrangement is, of course, independent of variations in the voltage of the battery.

Let T be the resistance of the thermometer coil, R_1 and R_2 those of the ratio coils, P that of the leads P, and C that of the leads C, and finally, let (R_3+x) be the resistance between the leads C and the bridge wire contact, where R_3 is the sum of the resistances of Z, BC, IB and R and x is the resistance between X and S, while a is that between the points XY. Then, when adjustment is obtained,

$$\frac{R_1}{R_2}=\frac{R_3+C+x}{T+P+a-x}.$$

It is usually arranged that R_1 and R_2 should be equal, and since P and C are equal it would follow that the coil resistance T is equal to R_3-a+2x. In order to make thermometers inter-

changeable the Cambridge Instrument Co. Ltd. arrange the resistance T so that it changes by one ohm, or ten ohms, between 0° C. and 100° C.

The Whipple indicator represented in Fig. 14 is a convenient form of the Wheatstone bridge suitable for both laboratory and industrial purposes. The leads are connected to the terminals on the left in proper order as indicated by the letters

FIG. 14.—Cambridge Whipple temperature indicator.

on these terminals. The pointer or needle of the suspended coil galvanometer can be seen through a window. The adjustable resistance consists of a wire wound spirally on a drum which can be rotated by the handle on the right, and as the spindle of the drum is screwed the rotation causes the drum to travel endwise. A corresponding scale of temperatures is engraved on the drum and can be seen through a window. The length of the scale is approximately 18 ft. from 0° F. to

2000° F., and thus the average length of 1° F. is over $\frac{1}{10}$ in. The instrument is used in the following manner—All the connections having been made as described, the battery tapping key is pressed to make contact for an instant and if a correct balance has been obtained the galvanometer needle remains stationary. Usually, of course, an adjustment of the drum is necessary to secure a balance, and the direction in which it should be turned to secure the balance is indicated near the galvanometer needle, i.e. if the needle moves over in one direction the true temperature is higher than that indicated on the scale of the drum and the drum is turned accordingly, while the movement of the needle in the opposite direction indicates a lower temperature. This procedure is gone through after each movement made in the drum until a balance is obtained, care being taken not to keep the tapping key in contact for more than an instant so as to ensure a long life for the batteries and to avoid any appreciable change of resistance of the various resistance coils and the thermometer coil due to the slight heating effect of the flow of current from the battery when the circuit is complete.

The adjustment rheostat, R in Fig. 13, is provided by which the coil resistances can be altered slightly to bring the reading on the drum into unison with the actual temperature when the thermometer is at some particular temperature, say, 0° C. Levelling screws are also provided as well as an adjustment for bringing the galvanometer needle to the centre of the scale when neutral. The ice-bobbin for the particular thermometer in use may be connected on the indicator or inserted in the leads C of Fig. 13. When the indicator lid is closed down it is arranged to depress a lever to hold the galvanometer needle so that the indicator can be moved about without undue risk of breaking the galvanometer suspension by excessive shocks.

The Whipple indicator is fairly accurate when suitable precautions are taken against dirty or damp conditions, and gives direct readings of temperature which makes it suitable for checking the readings of other thermometers in industrial works as well as in the laboratory.

Probably the most accurate method at the present time for the measurement of temperatures by means of resistance ther-

mometers is due to Sir F. E. Smith. The arrangement consists of a Wheatstone bridge where the lead connections can be interchanged or reversed. An outside view of this bridge is shown in Fig. 15 as made by the Cambridge Instrument Co., Ltd. By taking two readings of the thermometer resistance that of the leads is eliminated without requiring absolute equality. The reversal of the connections is made by means

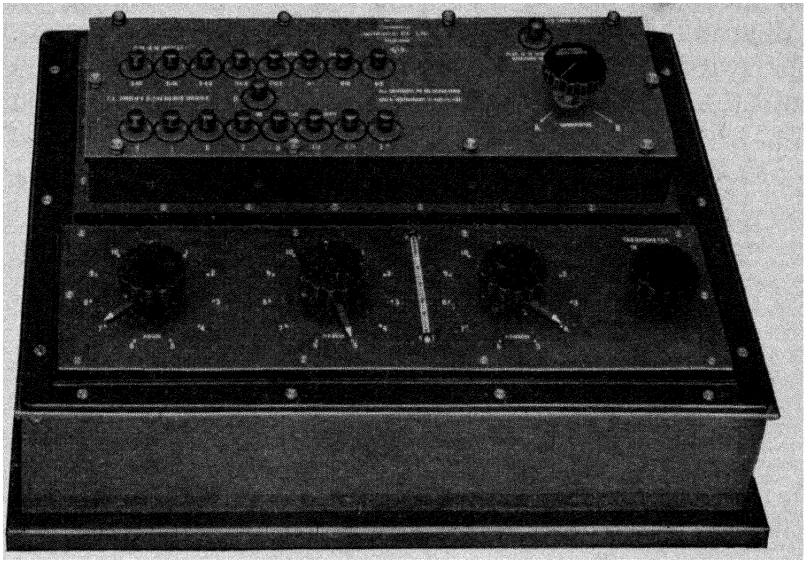


FIG 15.—Smith bridge

of a 6-pole mercury contact switch. A series of thirty shunted coils is used instead of a bridge wire, and, for the most accurate work all the bridge coils are immersed in oil circulated by a motor-driven stirrer. With due precautions the readings may be made with this bridge to $\pm 0{\cdot}002°$ C. over the range $-200°$ C. to $+600°$ C. ($-328°$ F. to 1112° F.). The temperature has to be deduced from the measured thermometer resistance by making use of the equations 1 to 5 on pp. 39, 40, and the corresponding equations on pp. 243, 244.

A method of measuring temperatures based on the potentiometer form of circuit is shown in Fig. 16. There are four leads L_1 to L_4 in this arrangement. The potential drop across the thermometer coil T is compared with that across the standard resistance R which has been compared with the potential of the standard cell SC. The adjustable resistance

R_1 is set to give a suitable small current from the battery B_1 through the resistance CW. With the switch S at contact 1 the contact Y is moved until the potential drop X to Y equals that of SC as indicated by the neutral reading of the galvanometer G. The resistance R_3 is adjusted to give a suitable current from the battery B_2 through the leads L_1 and L_4 and the shunt across L_1 through R, L_2 and T. The switch S is moved to contact 2 and the contact Y then shifted along CW until the new potential drop XY is equal to that across R. The switch S is now moved to contact 3 and Y again moved until the potential drop XY is equal to that across the coil T.

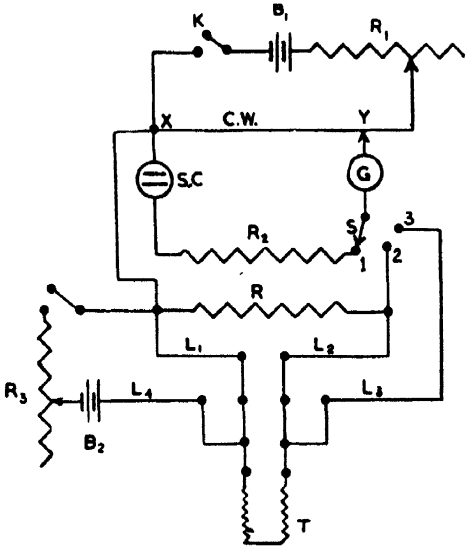


FIG. 16.—Potentiometer circuit.

Thus the resistance T is deduced from the known resistance R in proportion to the respective values of XY. If the resistance of CW per unit of length is known a check is given on the resistance R.

The three-lead method of compensation for the variable resistances of the leads in resistance thermometers was used originally by Sir W. Siemens. One arrangement is shown in Fig. 17. If the resistances of the leads L_1 and L_3 are equal, then, when the galvanometer G is neutral,

$$\frac{R_1}{R_2}=\frac{R_3+L_3}{T+L_1}$$

and $R_3=T$ if $R_1=R_2$.

It is evident that the positions of the battery B_1 and galvanometer G could be interchanged without affecting the scheme of operation. On calibration a scale of temperatures may be provided along R_3.

A modification of the three-lead arrangement favoured by some makers of industrial installations of the resistance thermometer is represented in Fig. 18. The coils R_1 and R_2 are connected by the bridge wire AD having a scale of temperature provided. When the voltage at C and at the point of contact

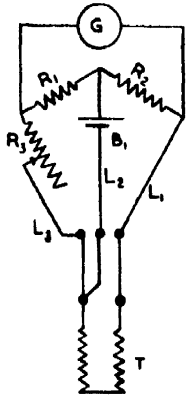


FIG. 17.—Three-lead compensation.

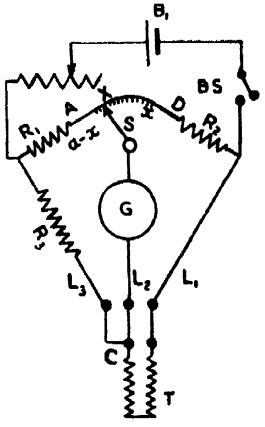


FIG 18.—Modified three-lead compensation.

X are equal the galvanometer G is neutral. Let a be the resistance of AD and x that of XD, then,

$$\frac{R_2+x}{R_1+a-x}=\frac{T+L_1}{R_3+L_3}.$$

Another modification represented in Fig. 19 is used by Leeds and Northrup Company, of Philadelphia, Pa., U.S.A. where the additional bridge wire EF is introduced of resistance b. The points of contact X and K are moved together by the same adjusting spindle so that, with the galvanometer G in balance,

$$\frac{R_1+a-x+y}{R_3+b-y}=\frac{R_2+L_2+x}{T+L_3}.$$

The scale on the slide wire AD is graduated in degrees of temperature. Three-pole switches are included at M, N and P.

The adjustment to the position of balance in these instruments requires some little time even with a skilled operator,

and instruments have been designed which indicate automatically the resistance or temperature of the pyrometer coil by the deflection of an indicator pointer over a scale. One arrangement of a cross-coil indicator designed by G. W. Harris for use with the four-lead compensated resistance thermometer is represented diagrammatically in Fig. 20.

This indicator arrangement reads in gas-scale degrees at all ranges of temperature, and its accuracy is independent of the voltage of the battery and of moderate variations in the lengths of the leads. The control or cross-coil K and the deflecting

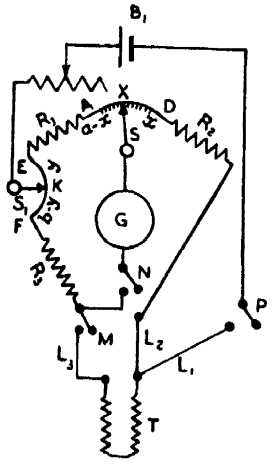


FIG 19 —Modified three-lead compensation

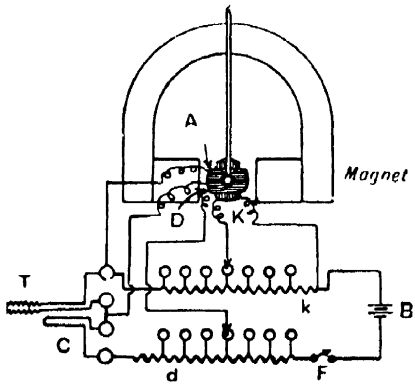


FIG 20 —Arrangement of Harris indicator

coils A and D are wound differentially at right angles to each other on a metal cylinder pivoted between the poles of the permanent magnet. A cylindrical iron core is enclosed by the coils without touching them and is stationary. The electrical connections to the coils are made by flexible ligaments which exert no control on the movement of the coils. The control coil K takes the place of a control spring by the moment or torque induced between the magnetic field of the coil and that of the magnet and is shunted with a resistance *k*, the value of which is determined by the sensitivity required, and may be made to vary simultaneously with the resistance *d* by means of a double-pole switch. One of the differential windings D is shunted by this resistance *d*, and the other differential winding A is shunted by the thermometer coil T.

The resistance *d* is variable to suit different temperature ranges of the instrument. These shunted windings are thus connected in series and the circuit is completed through the battery B and key F.

The indicator operates in the following manner : The resistance *d* is adjusted so that the two differential coils A and D balance each other at some particular resistance of the thermometer coil T corresponding to some particular temperature, depending upon the range of temperature to be measured. If the resistance of the coil T now increases owing to an increase of temperature the current through the winding A increases by an equivalent amount, and this causes a deflection of the pointer, which moves over the scale and thus indicates the temperature. The resistances *k* and *d* are made to vary simultaneously so as to compensate for the change of slope in the temperature-resistance curve of platinum at all ranges of temperature represented by eqn. 4 on p. 39. As mentioned previously the range of temperature at which the resistance *d* would be set would depend upon the temperatures to be measured. The object is to make the scale of the indicator very open, the instrument being thereby more sensitive than would be the case if only adjusted for the one range from the lowest to the highest temperatures for which the platinum thermometer is available. Moderate changes in the voltage of the battery B do not affect the reading of the indicator because the control coil K and the coils A and D are influenced in equal proportions for a particular setting.

In large installations of boiler and power plant, and in cold stores, chemical plant, oil refineries and in similar plant, it is the usual practice to measure the more important temperatures as an aid to efficient operation. Some of these temperatures may be measured by mercury thermometers, but in large industrial installations it may be rather laborious to have to go round a large plant to read and record ordinary mercury thermometers, and in some cases it may be difficult to gain access to all the thermometers. For such conditions electrical " distance " thermometers have been introduced consisting of resistance coils installed at the various points of measurement and wired to centrally placed indicators or recorders. In the standard type of thermometer, as built by the Cambridge

Instrument Co., Ltd., a length of annealed platinum wire of 100 ohms resistance at 0° C., is wound on a steatite spool and then glazed. The ends of the platinum coil are connected by short lengths of gold wire to insulated constantan leads brought to terminals in the porcelain head of the thermometer, for use from −300° F. to 1000° F. (−200° C. to 540° C.). The coil or resistor is usually enclosed in a copper, brass or steel sheath and in some cases may be slow in responding to varying temperatures. For such conditions, and to measure the mean temperature of a large enclosure from −100° C. to 140° C. the above firm can supply an arrangement where the wire is covered with silk and is supported in a thin-walled copper tube.

For measuring temperatures up to about 1000° F. Messrs. Leeds and Northrup Co. use platinum wire coil of resistance 10 ohms at 68° F. (20° C.) wound on a spool or core and enclosed in a metal or porcelain tube or sheath. For temperatures below 250° F. the resistor may be of nickel wire of 100 ohms resistance at 68° F. (20° C.) or copper wire of resistance 10 ohms at 77° F. (25° C.). When these thermometers are to be mounted in pipe lines, tanks or other locations where protection is necessary, the sheath may be accommodated in a metal well or pocket having a patented construction or mounting wherein the spool or core is pressed against the conical bottom of the sheath and the sheath also is pressed against the conical bottom of the well or pocket.

Some makers use the three-lead method of compensation while others prefer the two-lead non-compensating system. In the two-lead arrangement used by the Cambridge Instrument Co., Ltd., represented in Fig. 21, the thermometer coils T_1, T_2, T_3, etc., are each connected by the respective leads 1, 2, 3, etc., to the Wheatstone bridge with a common return l used to complete the circuits. R_1, R_2 and R_3 are standard resistances and an out-of-balance effect comes on to the single-coil indicator I according to the resistances of the coils T_1,T_2 or T_3, etc., brought into the circuit by the switch S. The balancing coils b_1, b_2, b_3, etc., are inserted in the respective circuits to bring all the thermometers and their leads to a standard resistance and thus to compensate for different lengths of leads. Variations of lead resistances due to tem-

perature are of little importance in industrial plant because the resistances of T_1, T_2, T_3, etc., tend to swamp small changes of lead resistances. Variations of battery voltage are allowed for by switching in the test coil *t* before taking readings of the thermometers and then altering the resistance R to bring the pointer to a fixed red mark on the scale of the indicator I.

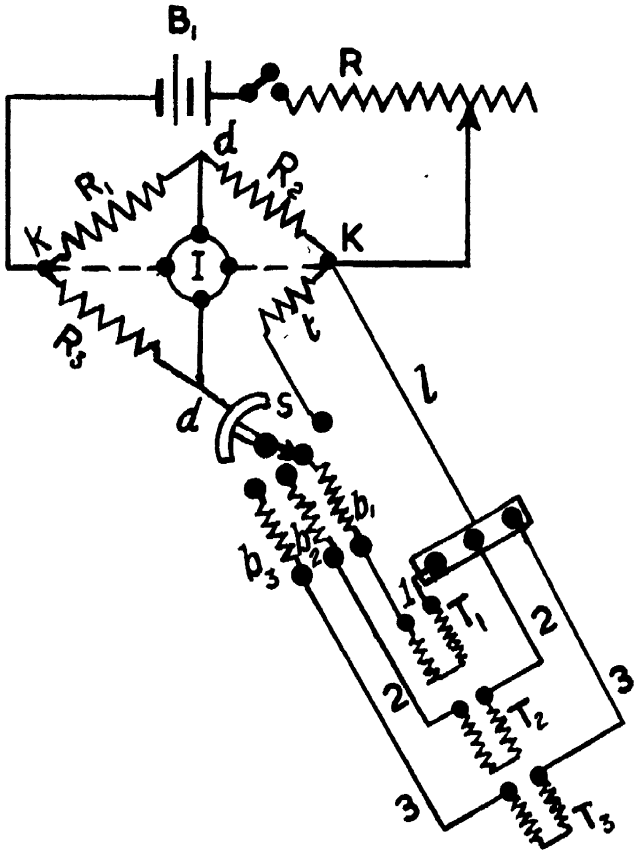


FIG. 21.—Distance thermometers.

Instead of using the battery B_1 the required d.c. voltage supply to the bridge circuit may be obtained from a.c. mains through a suitable transformer and rectifier unit, or from d.c. mains through a small rotary converter. In these arrangements the applied voltage may be sometimes subject to sudden variations which are likely to upset the readings on the single-coil indicator having spring control. The cross-coil type of indicator such as is represented in Fig. 20, p. 48, compensates

for moderate variations in voltage in the supply. With this system the coil *t* and variable resistance R would be dispensed with. The control coil K would be connected across the points *kk* of Fig. 21, while the coil A of Fig. 20 would connect the points *dd* of Fig. 21.

The general appearance of a multi-point indicator is shown in Fig. 22 for twelve points of measurement, as built by the Cambridge Instrument Co., Ltd. When the temperatures have to cover a wide range a double-range scale can be provided in the indicator. The lower portion of the casing accommodates the terminals and connections, balancing coils, selector

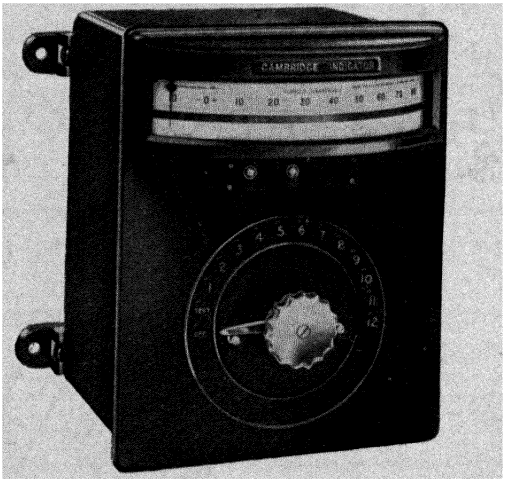


FIG 22.—Cambridge multi-point indicator

switch, battery and bridge, etc. For rough service a heavier pattern may be installed.

The measurement of the humidity of atmospheres in some industrial processes is a factor of increasing importance, and is closely connected with the measurement of temperature. The "absolute humidity" of an atmosphere of air or gas is the weight of water vapour contained in a unit weight of the air or gas. The warmer the air the more water vapour is it able to absorb. The governing principle is expressed by Dalton's law of mixtures, which states that each vapour or gas in a mixture without chemical action follows its own law of pressure, volume and temperature as if the others were not present, but the total pressure is the sum of each "partial"

pressure. Usually it is sufficient to measure the "relative humidity" expressed as a percentage of water vapour present compared with the amount of water vapour present when saturated at the same temperature, that is, having the maximum amount of water vapour which could be absorbed at the same temperature. Air which is not saturated is capable of absorbing more water vapour or moisture from surfaces in contact with the air, thus producing a drying effect, while conversely, absorbent materials may remove water vapour from the atmosphere and thus lower the relative humidity. Every humidity problem in industry is connected with these two effects and the object is to maintain a state of equilibrium best suited to the particular processes involved. For example, the control of the relative humidity may be required in such processes as colour printing, leather drying, textile manufacturing, drying of wood, paper, films, starches, etc., while air conditioning may have an important influence on the working conditions inside a building in hot climates or in hot processes.

Various methods have been devised to measure relative humidity. Some of these depend on the sensitivity of the dimensions or length of a strip of some substance to changes of humidity, such as human hair, animal membranes, wood fibres, etc., or to the absorbent qualities of certain hygroscopic salts or liquids. Probably the most reliable method is that based on the well-known wet and dry bulb hygrometer, making use of the principle of the lowering of the temperature of a surface from which water is being evaporated due to the latent heat required for the evaporation. The relative humidity may be estimated from the temperatures by the aid of factors based on experiment.

Ordinary mercury thermometers are not capable of giving meter readings or records of humidity, or of giving a means of controlling humidity. For this purpose Messrs. Elliott Brothers (London) Ltd. make use of electrical resistance thermometers arranged as shown in the sectional view in Fig. 23. Air enters at *f* and flows over the two dry bulbs *b* and then over the wet bulb *a* at a velocity not less than 5 ft. per second, leaving by the connection *e*. If this rate of flow cannot be easily obtained by connecting *e* to some

source of draught, a small induced draught fan may be required for this purpose. The passage round the wet bulb *a* is restricted in bore by a tubular block of heat insulating material. This

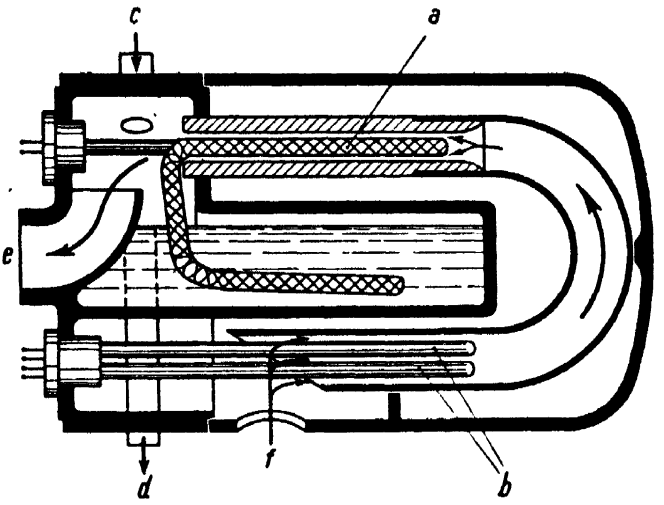


FIG. 23.—Resistance thermometers in humidity meter

wet bulb is moistened by a cotton wick or stocking dipping into a water reservoir which may be filled up with water at convenient intervals or preferably supplied with soft or distilled

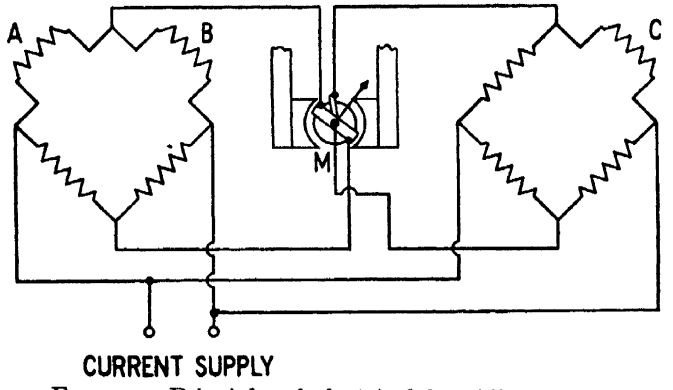


FIG. 24.—Principle of electrical humidity meter

water from a tank or cistern so as to allow a constant drip of water at the overflow *d*.

The measurement of the relative humidity is dependent on the dry bulb temperature of the air as well as on the difference between the wet and dry bulb temperatures. The method of measurement is represented in Fig. 24. In this instrument

the three electrical thermometers are inserted into two interconnected Wheatstone bridges where the out-of-balance effects are measured by means of a special cross-coil indicator M. The two dry bulbs are in the arms A and C while the wet bulb is in the arm B. All the resistances in the other arms are fixed in value. The resultant current in the diagonal coil of the indicator M is proportional to the difference of temperature between the dry bulb A and the wet bulb B, while the current in the other indicator coil is dependent on the temperature of the dry bulb C. By a suitable choice of the bridge resistances and of the circuit adjustments the indicator pointer is arranged to give the relative humidity. The two bridges are connected to the same source of current supply and thus readings are practically independent of small variations of the voltage supply. If a.c. mains supply is used a suitable transformer and rectifier is introduced. With the meter working in conjunction with an automatic regulator suitable valves, dampers and sprays may be controlled automatically for air-conditioning plants where a selected and adjustable degree of humidity has to be maintained.

Sources of Error.—It was mentioned previously that, in the Whipple indicator, the tapping key of the instrument should not be kept in contact for more than a moment so as to avoid errors which might be introduced by the slight heating of the platinum coil by the passing current. The error due to the heating effect of the current, however, is small and practically negligible for ordinary conditions of operation, as is shown by the following values,* where the normal current through the coil of a particular thermometer was 0·01 ampere.

Amperes through coil.	Heating of platinum coil above surrounding temperature, ° C.		
	At 0° C.	At 100° C.	At 444·5° C.
0·0025	0·001 ±	0·001 ±	—
0·01	0·011	0·01	—
0·05	0·41	0·41	0·29
0·10	1·65	1·69	1·20

* *Platinum Resistance Thermometry at High Temperatures*, Waidner and Burgess, U.S.A. Bureau of Standards. Reprint No. 124.

Further, the platinum thermometer as usually constructed is not adapted to follow changing temperatures very closely since it is nearly always necessary to use a sheath, and this of itself introduces an appreciable lag. Thus it is best suited for measuring a comparatively steady temperature. Care should also be taken that metallic vapours or furnace gases do not gain access to the platinum coil, or contamination of the platinum may result, with a consequent alteration of its resistance. Water vapour should also be excluded at low temperatures. Therefore a cracked or defective sheath should be replaced immediately. The value of the constant δ in the formula (4), p. 39, may be taken as a measure of the purity of the platinum in the thermometer coil, having a value near 1·5 for pure platinum. Within limits the same formula expresses the relation between the actual and platinum temperatures for impure platinum, but the value of δ is found to be greater than 1·5, and with impure platinum there is greater liability to a permanent change of resistance on being subjected to high temperatures than occurs with pure platinum, most probably due to the vaporisation of some of the impurities. The temperature corrections necessary with impure platinum coils were given on p. 40.

When a thermometer is placed in position the coil portion of the stem should be completely immersed, and this can be tested by noting whether various degrees of immersion have any appreciable influence on the observed temperature. It is always advisable to support the thermometer in a vertical position if it is not likely to be damaged by any operations conducted in the neighbourhood of the thermometer, but if it should be necessary to place it in a horizontal position with a considerable length of the heated portion projecting, the heated end should be supported. In any case, careful handling is always essential since the platinum coil and the insulation are fragile when subjected to high temperatures.

The various connections and leads are liable to introduce disturbing thermo-electric effects in the circuits, but this is only troublesome when the aim is to obtain a high degree of accuracy. With a sensitive galvanometer the thermo-electric effect, if any, can be seen by closing the galvanometer circuit when the battery circuit is open, and the error may be allowed

for by reversing the battery circuit and taking the mean reading of the measured resistance. The insulation of the connections, leads, galvanometer, etc., should prevent any accidental leakage from neighbouring lighting or power circuits from interfering with the reading of the instrument.

With reasonable care the platinum resistance thermometer is capable of great accuracy from low temperatures to the highest temperature for which it is suitable, and in fact it may be used to calibrate other types of thermometers with a fair degree of accuracy.

Care should be taken to keep all electrical connections and slider contacts free from dirt or moisture, or unknown and erratic resistances might be introduced and thus upset the accurate measurement of the resistance of the coil.

Apart from the question of thermometer errors the measurement of the temperature of gases flowing through a large boiler or similar plant may be subject to serious errors due to insufficient mixing of the gases and to the possible effect of radiations from the surrounding surfaces. This effect depends on the particular circumstances of each case in respect to the position of the thermometer, and on the temperature, velocity and transparency of the gases flowing past the thermometer. An asbestos shield mounted between the thermometer or sheath and the relatively "cold" heating surfaces without interfering with the flow of gases reduces the radiation error appreciably. Messrs. Bowen Instrument Co., Ltd., supply a special shield for the thermometer or pyrometer having an aspirator or ejector drawing a stream of gases through the shield, actuated by a steam jet or by an air blast supply. This type of arrangement is sometimes referred to as a suction thermometer or pyrometer.

A method sometimes adopted to reduce or perhaps eliminate radiation errors in special cases is to use two or more thermometers of different diameters in or near the same position and to deduce the probable true temperature for zero dimensions by extrapolation. This may also allow for the heating effect of high velocity fluids.

Thermistors.—This name has been given to a modern product which can be used to measure temperatures under suitable conditions in place of platinum wire resistances. A

thermistor consists of compounds of certain metals such as manganese, nickel, cobalt, uranium, and various oxides, which can be blended to give specified relationships between temperature and electrical resistance. The compounds are usually formed into a bead or a rod form, with connecting leads and terminals, and fired under controlled conditions. The thermistor is then used in the same way as a wire-wound resistance element, except that the temperature-resistance coefficient is negative, that is, the resistance decreases with rise of temperature. They can be made to cover various ranges of resistance allowing of wide variations of circuit design. The resistance at o° C. may be very high, several megohms, and therefore a thermistor is not interchangeable with a platinum or nickel wire coil. It may be used in the same way through a Wheatstone bridge circuit, but a higher voltage may be required to give the necessary instrumental readings. Apart from the possible use in registering the temperature of small " hot spots " in special cases there appears to be little to gain by using a thermistor instead of a wire resistance in an ordinary Wheatstone bridge circuit as the temperature sensitive element.

The Bowen Instrument Co., Ltd., of Leeds have adopted a patented system for using thermistors in temperature measuring equipments where a momentary but powerful a.c. impulse lasting only a small fraction of a second is applied through a Wheatstone bridge circuit with the thermistor element in one arm of the circuit. This avoids the excessive heating effect of heavy currents of long duration and the consequent effect on the recorded temperature, but still gives a strong enough force to deflect the indicator or recorder, or to operate the relays of a temperature controller, especially when amplifying circuits are used to magnify the impulse.

Thermo-electric Pyrometers : General Principles.— Experiment shows that if two dissimilar metal wires are joined together at the ends so as to make a complete circuit a current will flow round this circuit if one of these end junctions is at a different temperature from the other end. In other words, an electromotive force exists, acting in the circuit, which must be attributed to the difference of temperature and the physical properties of the metals. Peltier first showed experimentally that the electrical energy given by a thermo-

couple is obtained from the heat energy supplied to the hot junction, which is termed the " Peltier " effect. Lord Kelvin similarly showed that a small e.m.f. exists in an apparently homogeneous wire if two points in the wire are at different temperatures, that is, where a temperature gradient occurs. This is known as the " Thomson " effect, and seems to hold for all metals except lead. For instance, the small e.m.f. in a closed copper wire which is not at a uniform temperature acts so as to send a small current from the colder part to the hotter part. With iron the reverse of this is found to hold.

A common method of measuring a thermo-electric current is to connect a sensitive galvanometer G in the circuit, as represented in outline in Fig. 25. The two wires L_1 and L_2 forming the hot junction at H have their other ends connected to the terminals T_1 and T_2 respectively, and are then connected by the leads D_1, D_2 to the galvanometer. If both leads D_1 and D_2 are of the same metal the " cold " junction is taken to be at the terminals T_1, T_2. If D_1 and D_2 are composed of the same metals as L_1 and L_2 respectively the cold junction is then transferred to the terminals of the galvanometer G. If the scale on G reads temperatures directly the instrument is usually termed an " indicator." The two wires forming a junction may be connected by welding, brazing or soldering without affecting the e.m.f. due to the couple, provided that the metals of the wires do not become contaminated. To make practical use of thermocouples for the measurement of temperatures it is obvious that the wires used should maintain a consistent relationship between the temperatures and the e.m.f. or the equivalent current. Under prolonged or repeated heating, physical changes in the metals may take place, and this effect limits the number of metals available. The standard temperature for the cold junction is usually taken to be 32° F., or 0° C. In practice it may not be convenient to maintain the cold junction at this temperature, and it then becomes necessary to compensate for the actual cold junction temperature if it differs from that existing at the calibration.

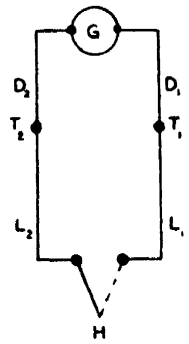


FIG. 25 —Thermocouple with galvanometer.

For some purposes it may be convenient to connect many thermocouples in series, as represented diagrammatically in Fig. 26. This combination is then termed a " thermopile " ; and the resultant e.m.f. is the sum of the separate values in the series.

It was Seebeck who made the discovery in 1822 that when a junction of two dissimilar metals is heated an electromotive force is developed. A few years afterwards Becquerel first proposed to use this method for measuring temperatures, and he employed a platinum-palladium couple. Pouillet used an iron-platinum couple, which he compared with an air thermometer. Edmund Becquerel resumed the study of his father's couple (platinum-palladium), and he was the first to direct attention to the necessity of using a galvanometer of high resistance so that any change of the resistance of the heated end of the couple would be practically inappreciable when compared with the total resistance of the circuit.

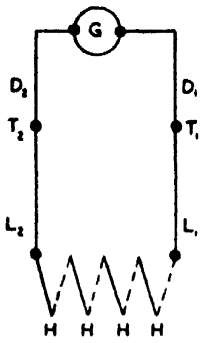


FIG. 26 — Thermopile with galvanometer.

The results obtained by the various experimenters were discordant until Le Chatelier, about 1886, and Barus and Tait about 1881, took up the study of thermojunctions and placed them on a reliable basis. Their investigations showed that the principal source of error was due to lack of physical or chemical homogeneity of the metals used up to that time. For instance, Barus showed that iron, nickel, palladium and their alloys may be unsuitable for the measurement of high temperatures on account of their liability to contamination, or to physical changes introduced by hardening and annealing, which may cause parasitic or localised currents to develop, and these may interfere seriously with the e.m.f. due to the thermojunction proper. Barus was led to adopt the (platinum, platinum 90%—iridium 10% alloy) junction for high temperatures. Le Chatelier showed that platinum-rhodium (10% rhodium) was a very stable alloy at high temperatures and used it in conjunction with platinum.

The modern standard thermocouple is now the platinum, platinum-13% rhodium for temperatures from −200° C. to 1500° C. (−392° F. to 2732° F.).

Owing to the high cost of platinum and its alloys thermo-couples made of relatively cheap "base" metal wires are in common use, such, for instance, as silver-constantan, copper-constantan, iron-constantan, and Hoskins couple of nickel, nickel-chromium. Constantan is an alloy wire of copper 60% and nickel 40%, sold commercially as a resistance wire. Silver-constantan is probably the most satisfactory of the base metal couples below a temperature of about 700° C. (1292° F.). The iron-constantan and copper-constantan couples are fairly satisfactory at temperatures below about 800° C. (1472° F.) and 500° C. (932° F.) respectively. The Hoskins (Ni, Ni-Ch) couple may be used up to about 1100° C. (2012° F.) when the wires have been carefully annealed, and up to 1300° C. (2372° F.) for short periods. Other couples of the nickel-chromium series are available under trade names such as chromel-alumel, titan, etc.

Although the (platinum, platinum-rhodium) thermojunction or couple is more reliable as regards the permanency of readings than any of the other couples, the e.m.f. developed at a given temperature is in general less than the e.m.f.'s given by the base metal couples and therefore necessitates a more sensitive galvanometer to give the same degree of accuracy in the readings. The following table * indicates the approximate relation with the cold junction temperature in all cases at 0° C.

	E.M.F. in millivolts (cold junction at 0° C.) = e.								
t temperature ° C.	100.	200.	400.	600.	800.	1000.	1200.	1400.	Exposure conditions
− + Pt/Pt-Rh 13% . . .	0·645	1·45	3·385	5·56	7 945	10·515	13·21	15·975	Requires protection
+ − Copper/Constantan . .	4·33	9·35	21·08	—	—	—	—	—	—
+ − Chromel/Alumel . . .	4·1	8·13	16·39	24·9	33·31	41·31	48 85	55 81	Oxidising or neutral
+ − Iron/Constantan . . .	5·6	11·2	22·5	34·2	47·3	—	—	—	Reducing or neutral

Thermo-electric Formulæ.—The relation between the electromotive force e and the temperature t of the above

* Cambridge Instrument Co., Ltd.

thermocouples is expressed approximately by a formula of the following form, first proposed by Holman,

$$\log e = a \log t + b \quad . \quad . \quad . \quad (1)$$

where a and b are constants depending mainly upon the metals used.

When the cold junction is maintained at 0° C. the following equations express the approximate relations for two of the thermocouples in general use, e being the e.m.f. of the thermocouple in microvolts, and t the temperature in deg. Cent.

(Platinum/platinum-rhodium 13%), $\log e = 1{\cdot}22 \log t + 0{\cdot}36$ approx.
(Copper/constantan) . . . $\log e = 1{\cdot}14 \log t + 1{\cdot}36$,,

When the formula (1) is applicable the thermocouple only needs to be accurately calibrated at two temperatures in order to determine the values of a and b. When the cold junction is at 0° C. equations of the form $e = a + bt + ct^2$ may also be used over a limited range to represent the relation between the e.m.f. e and the temperature t° C. and is given as a standard equation on p. 244. of the International Temperature Scale of 1948.

The above values of e and t imply that the thermo-electric power, $\frac{de}{dt}$, is positive throughout the useful range of the thermocouples. This, in fact, constitutes one of the advantages of these couples. With some thermocouples not in common use $\frac{de}{dt}$ becomes zero, and even negative, within their practical range of temperature, and e may again reach zero at some higher temperature. The use of these thermocouples should be avoided in common practice ; but on occasion such a couple has to be used in a particular problem, as is illustrated by Figs. 110 and 111 on pp. 227, 228, and there described.

One of the drawbacks in thermo-electric work has been the difficulty of reproducing wires to give the same e.m.f. at the same temperature from different ingots of an alloy. It is a considerable advantage in industrial practice to be able to replace or interchange thermocouples at any time without having to make a calibration. Messrs. Johnson, Matthey and Company, London, have succeeded in overcoming these

difficulties in platinum-rhodium and other alloys and they can supply the manufacturer of thermojunction pyrometers with material giving practically the same e.m.f. at the same temperature as that supplied a few years previously.

The usual construction of thermocouples or junctions as supplied for general purposes by the Cambridge Instrument Company is shown in Fig. 27, while Fig. 28 shows several methods of installing these for the measurement of high temperatures in a furnace. The wires forming the junction are insulated by thin porcelain sleeve insulators, and to prevent the wires from being contaminated or wasted by the action of furnace or flue gases, etc., a protecting sheath is used. For temperatures up to about 750° C. (1382° F.) an iron sheath may be sufficient, but beyond this temperature up to about 1400° C. (2552° F.) it is usually necessary to have a porcelain sheath glazed on the outside, or else to use a quartz sheath. In Fig. 27 the steel sheath forms a protection against accidental rough usage, but it would be removed for temperatures higher than about 750° C., or even for temperatures below this if changes of temperature were anticipated, so as to reduce the temperature lag of the thermometer.

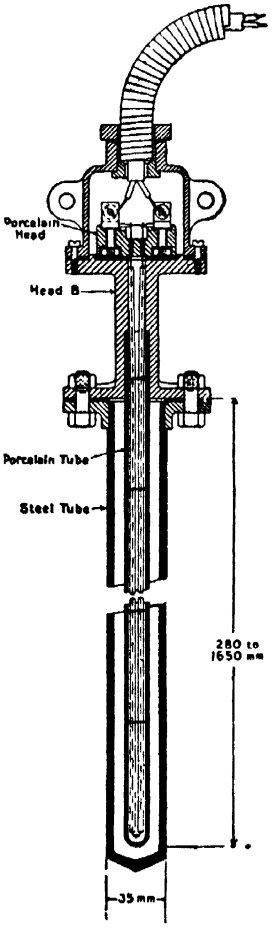


FIG 27.—Thermojunction with porcelain sheath and steel cover.

The base metal couples are similar in construction, but since they are mainly used for comparatively moderate temperatures an iron sheath may be sufficient if the couple is formed of wires. The materials being comparatively cheap, some makers also make the hot junction in the rod form, which is of robust construction and may not require a sheath.

The table on pp. 64 and 65 from the Wheelco Instruments Co. gives a list of materials generally available for pyrometer sheaths

or tubes under various conditions. For continuous duty the temperatures shown are the maximum recommended. For intermittent use the tubes may be used at slightly higher temperatures than shown.

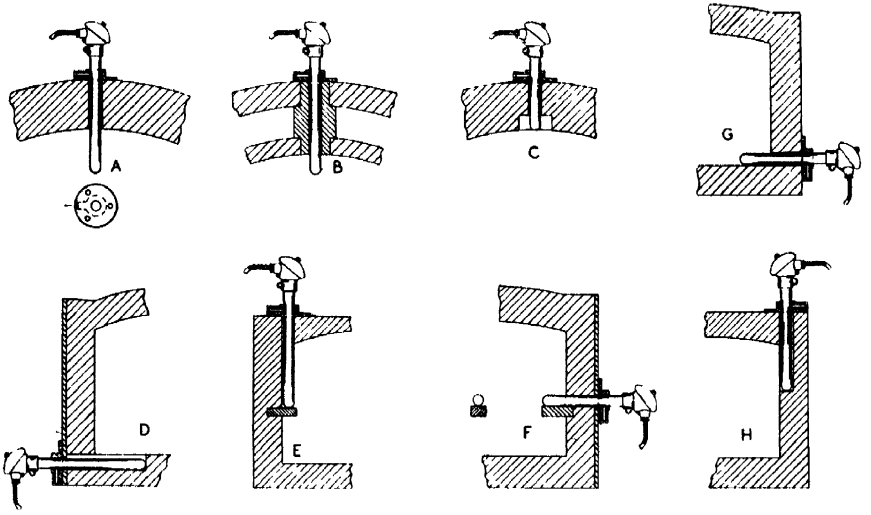


FIG. 28.—Methods of installing electrical pyrometers in furnaces.

Thermocouple pyrometers are available to measure or record surface temperatures such as calenders, paper mill rolls, etc. In the usual construction two dissimilar strips of metal are butt welded and mounted on a spring frame so that the hot junction can be brought into near contact with the surface. Where access is relatively easy the indicator may be mounted

Type of atmosphere or media.	Maximum temp., ° F.	Material of sheath or tube.
Natural or oxidising (ordinary heat treating)	2200	27% chromium iron
	2400	Pure nickel or porcelain
	2900	Porcelain
Neutral or reducing (carbon monoxide) (such as gas curtain hardening)	2200	27% chromium iron
	2400	Pure nickel or porcelain
	2700	Porcelain
Hydrogen, ammonia (such as bright hardening or brazing)	1000	Wrought iron or seamless steel
	2200	Inconel or pure nickel or porcelain
	2700	Porcelain
Nitriding	2200	Inconel or Nichrome

Type of atmosphere or media.	Maximum temp., ° F.	Material of sheath or tube.
Slagging or corrosive action (neutral or oxidising) (such as forging furnace or kilns)	2700	Silicon carbide
Slagging or corrosive action (neutral or reducing) (such as open hearth roof)	2500	Silicon carbide with inner Porcelain
Sulphur content	2000	27% chromium iron
Sulphur dioxide	2200	Inconel
Hydrogen sulphide	1000	Inconel
Lead vapours (rare metal refining)	2200	Inconel
Steam	2000	Inconel
Carburising	2000	27% chromium iron or inconel
Cyanide or salt bath	1750	Drawn chromium iron (specially treated)
Salt bath	2400	Same material as pot or inconel
Carburising salts	2000	Same material as pot or inconel
Dowtherm	—	Pure nickel or porcelain
Oil baths	—	Seamless steel or wrought iron
Glass	2800	Porcelain
Tin	—	Extra heavy wrought iron or seamless steel
Lead	1000	Extra heavy wrought iron or seamless steel
Lead	2000	27% chromium iron
Zinc (galvanising)	1000	Extra heavy wrought iron (put an open end pipe sleeve around the protecting tube. This should be changed when eaten through)
Brass (intermittent only)	2100	27% chromium iron
Brass or copper alloys (intermittent only)	2300	27% chromium iron
Aluminium	1500	Cast iron ; paint with whiting daily
Magnesium (Dow metal)	—	Extra heavy seamless steel or 27% chromium iron
Die-cast metals	1200	Cast iron or extra heavy wrought iron ; paint with whiting daily
Gas generating units	—	Inconel
Powder metallurgy	—	Inconel

NOTE : In general, heavier tubes should be used for excessive corrosion or abrasion. Other tubes, which have the same general characteristics, may be substituted for those recommended above.

also on the same frame, but when a long reach is required the strip would be mounted on a telescopic rod and the indicator, or recorder, placed some distance away with compensating

leads used to remove the cold junction away from the hot surface. For permanent installations the spring frame may be mounted on a swivelling rod.

The most important makers test each thermojunction and give a certificate for the constants of the junction, or for the payment of a fee the junction would be calibrated by the National Physical Laboratory or the U.S.A. Bureau of Standards. Makers are usually able to supply junctions which are interchangeable even though several years may intervene between the dates of manufacture.

The two wires forming the thermojunction should be welded or fused together. While it is true that the manner of contact between the two wires should make no difference to the electromotive force generated, when subjected to high temperatures a couple with the wires merely twisted together is liable to get loosened in course of time, and bad contact may result which increases the resistance of the circuit to an unknown degree. For high temperature measurements the best method of connecting the wires is to fuse them together at the extreme end in a flame after twisting the cleaned ends of the wires together for a short distance.

In respect to the welding of the hot ends the Wheelco Instruments Co., of Chicago, U.S.A., recommends the acetylene flame or torch, with the torch tip selected in proportion to the size of wire. For the smallest wires a No. 1 torch tip and for the largest wire gauges a No. 10 torch tip should be selected. Fasten the torch tip in a vice so that the flame is horizontal and adjust the torch to give a neutral flame about 4 in. long with the white cone surrounding the small blue cone—almost $\frac{3}{4}$ in. long. Hold the twisted junction or ends in the flame at the tip of the white cone until both wires are a bright red, and then dip in a fluxing mixture consisting of six parts of fluorspar to one of borax; or, if necessary, borax alone may be used. Place the flux-covered twisted ends immediately in the flame. Since one wire melts at a lower temperature than the other the weld should be manipulated in the flame until both wires reach their melting points at the same time, by keeping the wire which melts first in the cooler part of the flame until the other wire is about to melt, and then to revolve the weld in the flame until both metals

fuse together forming a ball weld at the tip. The flame should be moderately hot to prevent burning. After fluxing the metal the weld should be made on the first attempt, if possible, for continued heating at welding temperatures usually gives a poor weld. Only experience can provide the skill required to obtain the best results.

It is desirable to anneal the wires of the couple before the first calibration because any lack of physical or chemical homogeneity may set up parasitic electromotive forces and currents. Also, unless heated to nearly the melting point after manufacture, the e.m.f. of the couple is liable to change in course of time. The annealing can best be done by sending a heating current through the wires. The leads from the couple should be well insulated.

At moderate temperatures a couple may be tested against a standardised thermometer or thermocouple in a bath of well-stirred liquid, or, at the higher temperatures against a standardised thermocouple in an electric furnace. Or, again, it may be compared against fixed temperatures such as are given on pp. 244 and 251. The National Physical Laboratory state : " The accuracy to which a calibration is given depends on a number of factors such as the type and method of assembly of a thermocouple, the characteristics of an indicator if one is used, the length and upper limit of the temperature range. It is impossible to give a precise statement of the accuracy applicable to all tests."

Cold Junction Corrections.—It will have been noticed that the wires forming the hot junction are connected to the head of the thermometer and the galvanometer leads are commonly connected to the wires in the head by screwed contacts. Unless the head of the thermometer is specially cooled so as to preserve practically a constant temperature at this end it is evident that the terminals or connections at the head are likely to acquire a temperature higher than that of the outside leads and measuring instruments. Therefore care has to be taken that no incidental electromotive forces are developed at the thermometer head. Terminal connections should preferably be of copper, as brass is liable to cause parasitic thermo-electromotive forces under varying temperature conditions. If the external leads were of the

same materials as those forming the junction inside the thermometer no appreciable e.m.f. would then be produced at the thermometer head and the cold junction would now be at the outer end of the leads. For reasons of cost, however, it may be desirable to use outside leads of cheaper wire, and for use with the platinum series of couples Bristol and Peake independently proposed to use leads made of cheap alloys which happened to give practically the same e.m.f. as the platinum and its alloys within the limited range of temperature anticipated at the head or terminals of the thermometer.

For use with the platinum series of thermojunctions Peake

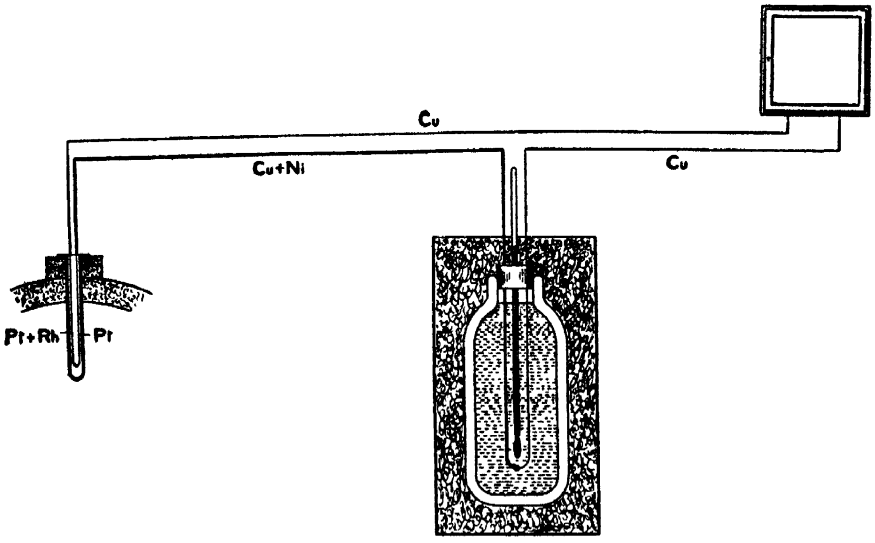


FIG. 29.—Peake's compensating leads.

introduced his compensating leads, one of copper and the other a copper-nickel alloy of suitable composition, giving the same e.m.f. as that given by the platinum and the platinum alloy at the same temperature. Experiments showed that the compensation is practically correct for any temperature of the thermometer terminals up to 300° C. The connections in this case are illustrated in Fig. 29. The copper lead has to be connected to the platinum alloy wire and the copper-nickel lead to the platinum wire of the junction to give the proper compensation. The cold junction is shown placed in a thermos flask filled with oil and with the leads well insulated. The temperature of the flask is read on the mercury thermometer,

which should show very little change of temperature even though the surroundings fluctuated several degrees. Most makers supply cold junction flasks or boxes, and, for a permanent installation, it is the best practice to place the cold junction in a vessel buried a few feet in the ground.

The compensating leads are particularly useful when the pyrometer is necessarily short and the pyrometer head acquires a fairly high and uncertain temperature, and also where the leads are long; for example, as in measuring the temperature of superheated steam at various points in a range of steam pipes in a central power station, or the steam temperatures at various positions in a large steam turbine, and making use of one galvanometer or indicator for all the pyrometers through a switchboard.

Unless the temperature of the cold junction happened to be that at which the calibration was made, corrections need to be applied to the readings of the indicator to allow for the cold junction temperature. One approximate method consists of setting the galvanometer or indicator needle at the temperature of the cold junction when on open circuit (the instrument being calibrated with cold junction 0° C.), but this method is somewhat troublesome. Instead of this a calculated correction may be made. If t_0 is the cold junction temperature for which the instrument reads correctly and t_1 the observed temperature of the cold junction, the correction usually lies between $\frac{1}{3}(t_1-t_0)$ and (t_1-t_0) depending upon the type of couple and the temperatures of both hot and cold junctions.* Commonly the pyrometer is calibrated for a cold junction temperature of 20° C. (68° F.).

For example,† in a (Pt, 90 Pt–10 Rh) Heræus couple it was found possible to correct for the cold junction temperature, t_1° C., by adding to the observed temperature t° C. the amount $0{\cdot}6t_1$ from 400 to 700° C. and $0{\cdot}5t_1$ from 700° C. to 1400° C., where t_1 was less than 50° C., and t_0 was 0° C. The automatic cold junction compensator is described on p. 119.

Potentiometer Method of Measuring Electromotive Force.—The galvanometer method previously described is

* *Measurement of High Temperatures*, Burgess and Le Chatelier.

† *Note on Cold-Junction Corrections for Thermo-couples*, Reprint No. 202 (from Bulletin of the Bureau of Standards, Vol. 9), U.S.A.

suitable for many technical and industrial measurements. It is usually necessary to have resort to potentiometer methods when a greater degree of accuracy than perhaps $\pm 10°$ C. at fairly high temperatures is required. In the potentiometer method use is generally made of a standard cell, or some other steady source of known e.m.f., and a suitable combination of known resistances together with a sensitive galvanometer. If E is the e.m.f. of the standard cell and R the total resistance in circuit with the cell, and if the thermocouple is connected in series with the galvanometer across the portion

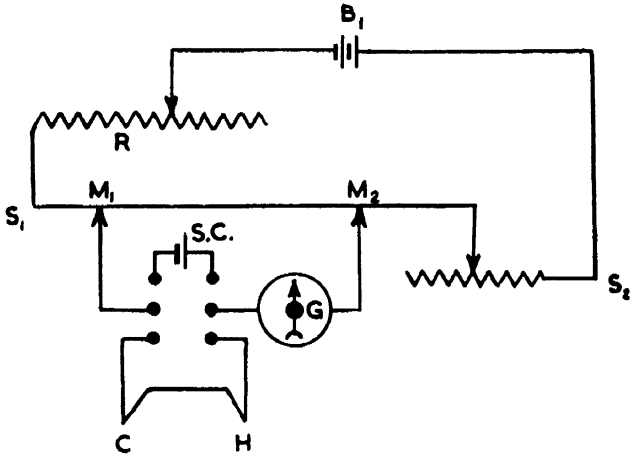


FIG. 30.—Potentiometer method of measuring e m f.

r of the total resistance R so that the galvanometer shows no deflection, then the e.m.f. of the couple is $\frac{Er}{R}=e$. The accuracy of this method is independent of the resistances of the leads and of the accuracy of the galvanometer.

In practice it is found preferable to balance a portion of a battery or storage cell circuit against the standard cell and then to use this portion of the battery circuit in place of the cell, the balance being obtained immediately before a reading is required. This arrangement is represented in Fig. 30. B_1 represents the battery in series with the variable resistance R in combination with coils and bridge wire represented by S_1S_2. Either the standard cell SC or the hot and cold junctions, H and C, can be placed in series with the galvanometer. The manner of operation is to connect the cell SC to S_1S_2 by shifting

the contacts M_1 and M_2. The resistance R is altered until the sensitive galvanometer G shows no deflection, and then it is known that the difference of potential E between M_1 and M_2 is that of the standard cell SC. This cell SC is now replaced by the hot and cold junctions, H and C, having an e.m.f. of value e, M_1 and M_2 being moved until the galvanometer again shows no deflection, a balance being thus again obtained. Then the ratio $\frac{e}{E}$ is proportional to the respective resistances M_1, M_2.

In practice the current through the battery B_1 and circuit is adjusted by the variable resistance R to 0·01 amp. by balancing the standard cell across a suitable resistance (for a cadmium cell of voltage 1·0185 the resistance is obviously 101·85 ohms). The resistance S_1S_2 in Fig. 30 may consist of, say, 100 equal coils each of resistance 0·01 ohm, giving a fall of potential across each coil of 100 microvolts. A bridge wire in series with the coils would also have a resistance of 0·01 ohm and suitably divided into, say, 100 divisions, each division representing 1 microvolt. Thus the main coils can be varied in steps of 0·01 ohm and the bridge wire used to give the necessary refinement between each step.

Potentiometers of the vernier type may be used to obtain fine adjustment of the resistance. One simple form designed by Dr. Harker has 20 coils, each of resistance 0·1 ohm, in series with 11 coils, each of resistance 0·01 ohm, in the battery circuit. If the battery current is adjusted to 0·01 amp. as before described, the drop of potential across each of the 20 coils is 1000 microvolts and across each of the 11 coils is 100 microvolts. A bridge wire of 0·02 ohm resistance may be shunted across any two of the eleven coils and is subdivided into 100 parts, and as this wire carries a current of 0·005 amp. each division represents 1 microvolt. The contacts for the various coils are made by mercury cups as these are more suitable for refined measurements of resistance than are plug contacts. Plug contacts have to be kept quite clean and generally have a slightly variable resistance according to the pressure used in placing them in contact, though quite suitable where extreme accuracy is not essential. The thermocouple is connected in series with a sensitive galvanometer across from one

of the 20 coils as selected and the bridge wire, and adjustment of the points of contact are made until the galvanometer registers a balance.

Portable thermocouple potentiometers are available in a compact form for standardising or checking indicators or recorders. Fig. 31 gives a perspective view of one made by Elliott Brothers (London) Ltd. It is completely self-contained with a sensitive galvanometer, standard cell, resistances and dry battery, etc. Two ranges are provided, 0–30 and 30–60

FIG 31.—Portable potentiometer.

millivolts, and the smallest scale division represents 0·01 millivolt or 10 microvolts, which should enable estimates to be made to the nearest microvolt. The circuit contains 29 coils each equal to a potential difference of 1 millivolt, and a slide wire of 1·1 millivolts. By arranging the dials of the coil switch and slide wire in concentric form a scale length of about 9 in. for 1 millivolt is obtained. The change of range is effected by means of a plug.

Although the galvanometer G in Fig. 30 may be very sensitive usually there is some little difficulty in finding the true potential

balance. If time permits it is always advisable to adjust M_1 and M_2 so that the galvanometer indicator is displaced slightly from the neutral position, first in one direction and then in the other by an equal amount, and then to half the difference. Unless the potentiometer connections are all at the same temperature a slight disturbance may be caused by thermo-

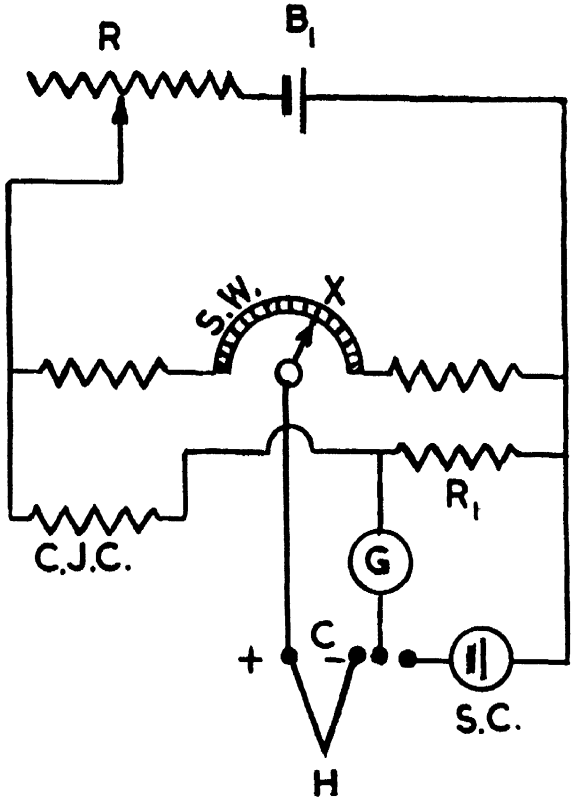


FIG. 32.—Potentiometer system (Leeds and Northrup Co.).

electric effects at some of the connections. This influence may be practically eliminated, however, when taking a reading by reversing the battery and thermocouple connections simultaneously and then taking the mean of the two sets of readings.

Leakage from nearby furnace or lighting circuits into the potentiometer circuit may be detected by short-circuiting the thermocouple with the battery circuit open, and observing the galvanometer for any deflection.

Messrs. Leeds and Northrup Co. use a modification of the potentiometer system, represented in Fig. 32. The potential

drop across the resistance R_1 is adjusted to that of the standard cell SC by altering the resistance R until the galvanometer G is neutral. The thermocouple is then connected across the point of contact X on the slide wire SW and the connection between R_1 and the cold junction compensator coil CJC. If the galvanometer needle moves from the neutral position an automatic mechanism, to be described later on p. 154, moves the slide wire contact X until the balance is again established. The temperature scale is given on the slide wire SW or shown on the inked chart of the recorder. The same automatic

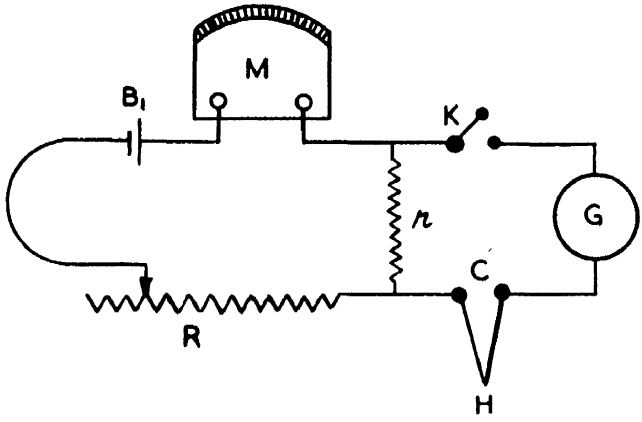


FIG. 33.—Holman's modification of potentiometer.

arrangement is used to operate the temperature controller when required.

The modification illustrated in Fig. 33 was first used by Holman. B_1 is a storage cell, M a milliammeter, R an adjustable resistance, H and C the hot and cold junctions respectively, G a sensitive galvanometer, preferably of the mirror type, r a fixed resistance (usually 0·1 ohm). Thus this method does not require a calibrated resistance box or potentiometer or standard cell, but uses a calibrated milliammeter or indicator M instead together with one or more known resistances. The object is to obtain the e.m.f. between the two ends of the known resistance r, which will be equal to the resultant e.m.f., e, of the hot and cold junctions when adjustment is obtained so that no current flows through the galvanometer G, and then to read the current flowing through the milliammeter M. This

current, of course, also flows through the known resistance r therefore,

$$e = \text{current} \times \text{resistance}.$$

The scale of the apparatus is altered by substituting different values of r.

The relations between the e.m.f. of value e and the temperature of the thermojunction would be known from previous calibrations at known temperatures, or for approximate work with the platinum series of thermojunctions it may be suffi-

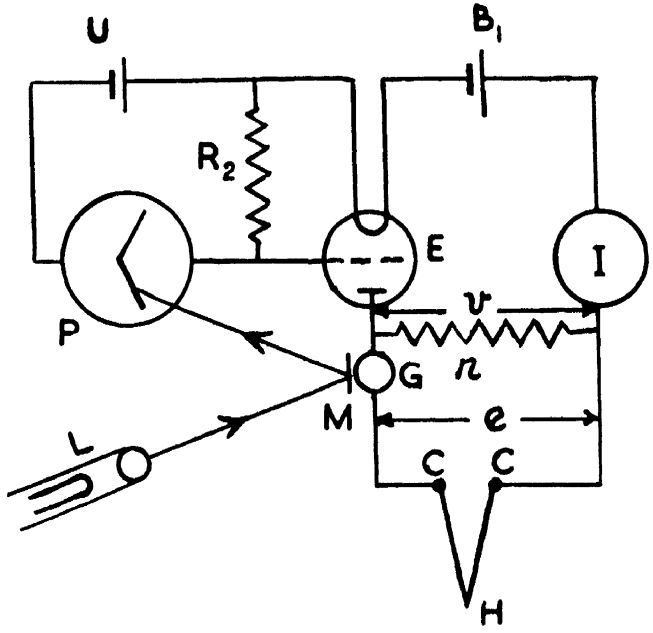


FIG 34 —Automatic potentiometer (Bowen Instrument Co Ltd.).

cient to calibrate at two known temperatures within the region in which the junction is to be used with the cold junction kept at some standard temperature, say, 0° C., and then to make use of the Holman formula, p. 62. In the industrial type of this potentiometer the indicator M may have the scale graduated in terms of temperature by calibration.

An increase in the temperature of the hot junction H usually means an increase is required in the current through r and M by a reduction of the resistance R. Messrs. Bowen Instrument Co. Ltd. make use of an electronic potentiometer whereby the circuit resistance equivalent to R is altered automatically to preserve a balance. The arrangement is represented in Fig. 34.

The variable resistance R of Fig. 33 is replaced by the thermionic valve E of standard type. Within limits the internal resistance of this valve decreases as the grid voltage is raised, and for this purpose the sensitive mirror galvanometer G with mirror M is used to deflect a beam of light issuing from the small projector L on to a photo-electric cell P, operated through the rectifier U. A high resistance R_2 is inserted between the grid and the filament of the amplifying valve E. In operation the mirror galvanometer GM is set so that for zero input voltage ($e=0$) the spot or circle of light falls near the edge of the photo-cell cathode and the cell has the maximum of illumination, which gives a negative grid voltage, and thereby any anode current of the valve is suppressed. If the thermocouple now develops a voltage e the spot of light tends to move off the edge of the cathode of P, thereby decreasing the photo-cell illumination, and causing an increase in the grid voltage and anode current, which results in an increase in the voltage v across the resistance r to oppose the voltage e of H until the spot of light moves back towards the photo-cell cathode. The anode current in E required to produce this result is proportional to e and is shown by the indicator I. Equilibrium is reached when the voltage v balances the input voltage e except for the small difference across the galvanometer G required to move the spot of light by a few millimetres, and the reading error due to this is not more than a fraction of 1% even for an input voltage e of one millivolt. Any desired range may be arranged by a plug and socket alteration in the value of r. An electrical range setter and an automatic cold junction compensator can be provided if required in the installation.

Standard Cells.*—The Clark cell has been used as a standard of electromotive force for potentiometer work on account of its constancy. Such a cell can be constructed from a small test tube, closed by a cork through which passes a glass tube containing a platinum wire. A quantity of pure redistilled mercury is placed in the tube so as to cover the end of the platinum wire, and on the mercury rests a paste made by mixing together mercurous sulphate, saturated zinc sulphate,

* For detailed instructions regarding the construction of standard cells reference could be made to any standard work on Electricity or Electrical Testing.

and a little zinc oxide to neutralise it. A rod of pure zinc passes through and is fixed by the cork so as to dip into the paste. The top of the test tube is then sealed with marine glue.

The e.m.f. of the cell at 15° C. is 1·434 volts, decreasing by about 0·08% for each rise of 1° C.

The cadmium cell was proposed by Weston on account of its small temperature coefficient and it has now become the standard of reference. In this cell the zinc of the Clark cell is replaced by cadmium, and the negative electrode, instead of being zinc, is made of an amalgam containing about twelve parts of cadmium in a hundred parts of the amalgam. A saturated solution of cadmium sulphate replaces the zinc sulphate of the Clark cell. The rest of the cell is the same.

The e.m.f. E volts of the cadmium cell is at t° C.

$$E = 1{\cdot}0183 - 0{\cdot}000{,}040{,}6(t-20) - 0{\cdot}000{,}000{,}95(t-20)^2 + 0{\cdot}000{,}000{,}01(t-20)^3.$$

When using a standard cell no appreciable current should be allowed to pass through.

CHAPTER IV

TOTAL RADIATION, OPTICAL AND PHOTO-ELECTRIC PYROMETERS

Laws of Radiation.—The molecules of which a radiating body is composed are in a state of rapid motion or vibration, each according to its nature and temperature, and send out radiations of various wave-lengths. The molecules are also capable of absorbing radiations for which it is their nature to respond falling on them from molecules situated deeper in the body or from some other radiating or reflecting body. The radiations are taken to be electro-magnetic in origin ; but at low temperatures the radiations are mostly of heat having relatively long wave-lengths, while at high temperatures light is also emitted of shorter wave-lengths. Whatever may be the physical constitution of the various radiations, whether of waves or particles or a combination of these, there is fairly conclusive evidence of the similarity of all these radiations in respect to the velocity of propagation, the laws of reflection, diffraction, polarisation, interference, etc. When these radiations fall on another body of matter a response may be excited in some or all of the molecules of the body and radiant energy thereby absorbed ; or again, some of the radiations may be reflected from the surface of the body and some may pass through the body. A good radiator is found to be an equally good absorber of radiations, while good reflectors and transparent bodies are poor radiators and equally poor absorbers of radiant energy. Common experience suggests that different substances may differ greatly in their radiating or absorptive powers and that some standard of comparison is necessary. The usually accepted standard is what is termed a " black body," or a body having " full radiations " and was originally defined by Kirchhoff as " A body which is not in the least transparent, and which does not reflect at all, but absorbs all incident radiations of whatever wave-length at every temperature." The radiations from carbon or lamp-black nearly fulfil " black body " conditions,

but most other substances are less perfect in this respect, or, in other words, their relative emissivities or emissive powers and their absorptive powers are less than unity when compared with a black body. This feature is discussed later on p. 80. It may be shown, however, from a consideration of the theory of exchanges, that the radiations coming from a small hole in an enclosure at a *uniform* temperature fulfils black body conditions whether or not the surfaces inside the enclosure radiate as black bodies.* This condition of uniform temperature rarely quite holds in ordinary furnaces in practice. In the open hearth steel furnace, for instance, the inside walls

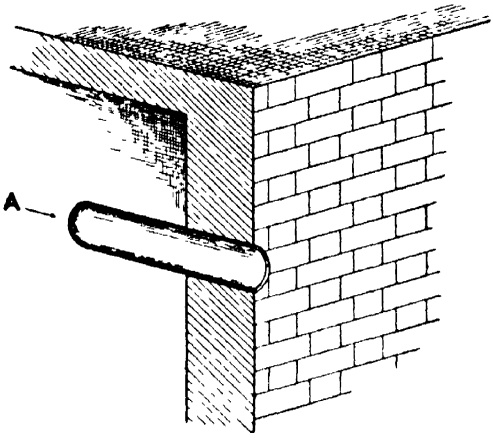


FIG 35.—Closed tube in furnace for radiation pyrometers

may not have the same temperature all over, and may be lower than the gas temperatures. Again, the walls of a boiler furnace may have a temperature much below that of the gases. In practice the radiation coming from the bottom of a closed tube, such as is shown in Fig. 35, may be taken to fulfil black body conditions as far as the temperature of the tube is concerned, but it should be understood that the temperature of the tube may be higher or lower than that of the gases in contact with it if the tube can "see" radiating walls having temperatures higher or lower than that of the gases.

The Stefan-Boltzman fourth power law of total or "black body" radiation is partly based on theoretical calculations but is substantially confirmed by experiment. It states that the

* Refer to Preston's "Theory of Heat."

total energy radiated by a "black body" per unit of time is proportional to the fourth power of the absolute temperature. This relationship has no reference to the temperature of any other body, but it may be observed that the surface of a black body at the absolute temperature T enveloped by a surface having an absolute temperature T_0 would lose energy by radiation at the net rate per unit of time proportional to $(T^4-T_0^4)$. For example, if T is 2000° C. abs. (1727° C.) and T_0 is 473° C. abs. (200° C.) the net loss by radiation from the hot surface of the black body would be proportional to (2000^4-473^4) or $\propto(160{,}000-500)10^8$. This result indicates that the envelope at 200° C. has hardly any practical influence on the loss of radiant energy by the black body at 1727° C.

Radiation pyrometers are usually calibrated for black body conditions and therefore give black body temperatures. It follows that the true temperature of the sighted object would be higher than the recorded black body temperature if the object does not fulfil black body conditions. For instance, the surface of a solid or liquid metal in the open does not fulfil these conditions. Such surfaces are sometimes said to be "grey" or "selective." The effect is usually expressed in terms of the relative emissivity E_r of the surface relatively to that of a black body, where E_r may be defined in the following terms. Let I be the net loss of radiant energy per unit of surface and time by a black body at the true absolute temperature T, and I_1 the corresponding net loss of radiant energy at the measured black body temperature T_1 abs. Then, by definition,

$$E_r=\frac{I_1}{I}=\frac{T_1^4-T_0^4}{T^4-T_0^4} \quad . \quad . \quad . \quad (1)$$

where T_0 is the absolute temperature of the surrounding enclosure. The T_0 term can usually be neglected in radiation pyrometers, and then,

$$E_r=\left(\frac{T_1}{T}\right)^4 \quad . \quad . \quad . \quad . \quad (2)$$

This expression for E_r does not imply that a surface which does not fulfil black body conditions necessarily emits total radiations proportional to the fourth power of its absolute temperature. For instance, the index for polished platinum is

near to 5, while the index for gases is usually less than 4. The following table illustrates the relationship of actual temperatures with those observed by means of a radiation pyrometer.* The values of E_r have been added.

READING OF RADIATION PYROMETERS SIGHTED IN OPEN

Black body observed temperature	True temperatures and values of E_r.											
	Molten copper.		Molten iron.		Copper oxide.		Iron oxide.		Nickel oxide.		Platinum.	
°C.	°C.	E_r.	°C	E_r.	°C	E_r.	°C	E_r.	°C.	E_r	°C	E_r.
600	1130	0 15	—	—	720	0 600	630	0 87	710	0·62	1160	0·138
800	—	—	1200	0 282	945	0 605	835	0 88	895	0 72	1430	0·158
1000	—	—	1475	0·282	1170	0·605	1040	0 88	1075	0·80	1695	0·175
1200	—	—	1750	0 282	—	—	1250	0 88	1255	0·87	—	—

When a steel ingot is taken from a furnace a scale of iron oxide of variable thickness soon covers the surface of the ingot. The surface of the oxide is not far from black body conditions, as is shown in the accompanying table, but the scale is a poor conductor of heat and the surface may fall rapidly in temperature below that of the metal underneath. According to Burgess and Foote the difference may be 12° C. at 600° C. and about 80° C. at 1000° C. These results probably have reference to a thin scale of iron oxide as differences of over 100° C. have been noted by other observers at about 1000° C.

The radiation from hot gases or flames is usually much below that for black body conditions, and depends upon many factors not easy to assess in practice except in a general way. The radiation from non-luminous gases is due mainly to the presence of carbon dioxide and water vapour, and the greater the partial pressure of these gases, the greater the thickness of the body of gas, and the higher the temperature, the greater is the radiation. The radiation from luminous gases is usually higher than for non-luminous gases at the same temperature, especially when particles of carbon are present. If further information is desired on the significance of radiation in engineering practice reference may be made to the paper on

* Scientific Paper No. 250, *Characteristics of Radiation Pyrometers*, Burgess and Foote, Bureau of Standards, U.S.A.

"A Review of Recent Progress in Heat Transfer" by Prof. C. H. Lander.*

Total Radiation Pyrometers.—The energy received by a total radiation pyrometer is usually estimated by directing the energy on to a suitable receiver, generally a small blackened disc. The temperature of the receiver increases nearly in proportion to the energy received, and this is commonly estimated by a thermojunction or a series of junctions fixed to the receiver, and connected to an indicator or potentiometer in the manner described in Chapter III.

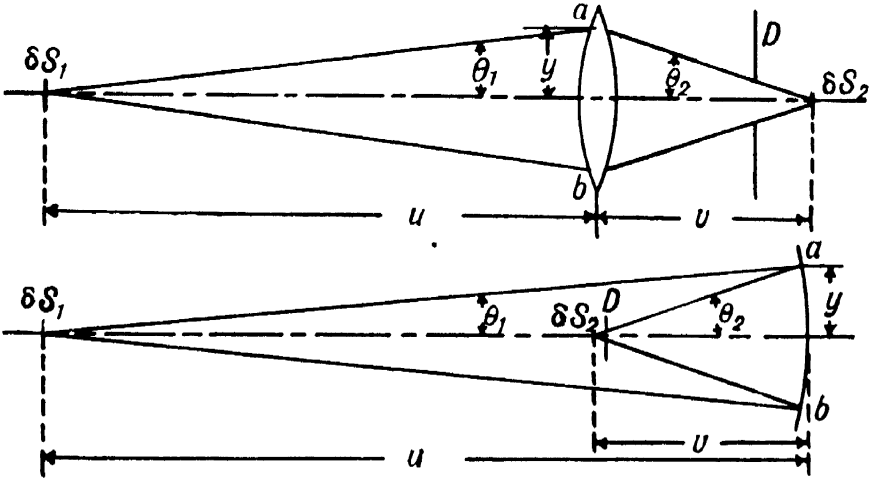


FIG 36.—Radiation pyrometers of variable focus

The quantity of energy falling on the receiver not only depends upon the temperature of the source, but also on the area of surface of the source and of the receiver, on their distance apart, and on their emissive and absorptive powers. In general it is desirable to have the receiver as small as is practicable, principally because the necessary area of the source is thereby correspondingly small; but with a small receiver some condensing arrangement is necessary to concentrate the energy at the surface of the receiver. This is usually obtained either by a convex lens or by a concave mirror, and two different designs of instrument are then possible.

1st. The source and the receiver are located at the conjugate foci of the lens or mirror.

* *Proc. Inst. Mech. Engrs.*, 1942, Vol. 148, No. 3. Also refer to "General discussion on Heat Transfer" *ibid.* Sept. 1591.

2nd. A front diaphragm of the pyrometer and the receiver are located at the conjugate foci of the lens or mirror.

For general service it is fundamentally important that the pyrometer reading should, within limits, be independent of the distance from the source to the receiver, and this necessitates a constant value for the solid angle of the cone of rays from the source ultimately falling on the receiver. To fulfil this condition in the first case the pyrometer has to be provided with a focusing arrangement whereby the distance from the lens or mirror to the receiver may be varied to suit the distance from the source to the lens. In the second case the front diaphragm becomes the secondary source and the foci are definitely fixed; therefore no focusing adjustment is required in this arrangement.

Case No. 1. Fig. 36 illustrates the conditions in the lens and mirror types of radiation pyrometers with variable focus.

Let δS_2 = area of receiver.

δS_1 = area of cross-section of source of which δS_2 is the image.

u = distance of source from lens or mirror.

v = distance from image to lens or mirror.

i_1 = intensity of the radiation of the source.

Then, the total energy I_1, in the cone $a\,\delta S_1 b$ is given by,

$$I_1 = 2\pi i_1\,\delta S_1 \int_0^{\theta_1} \sin\theta\cos\theta\,\delta\theta = \pi i_1\,\delta S_1 \sin^2\theta_1 \quad . \quad (3)$$

A similar expression applies to the image space,

$$I_2 = \pi i_2\,\delta S_2 \sin^2\theta_2 \quad . \quad . \quad . \quad (4)$$

If there were no loss of energy by absorption and reflection, eqns. 1 and 2 would be equivalent. By the condition of magnification of the optical system $\frac{\delta S_1}{\delta S_2} = \frac{u^2}{v^2}$, and since $\sin^2\theta_1 = \frac{y^2}{u^2}$ nearly, and $\sin^2\theta_2 = \frac{y^2}{v^2}$ nearly, then $i_2 = i_1$ nearly.

When some of the radiation is absorbed by the lens or mirror (and reflected also in the case of the lens), i_2 is less than i_1. For all practical purposes, however, i_2 may be taken to be proportional to i_1.

Thus, $$I_2 = ci_1 \sin^2 \theta_2 \quad . \quad . \quad . \quad . \quad (5)$$

where c is a constant for each type and design of instrument.

Therefore I_2, the radiation absorbed by the receiver, cannot be independent of the focusing distance unless $\sin^2 \theta_2 = \text{constant} = \frac{y^2}{v^2}$ (nearly).

In the second case $\sin^2 \theta_2$ is made constant by fixing the angle θ_2 at a constant value by means of a diaphragm or pupil D in Fig. 37 at a certain distance from δS_2, and when this is done, the energy falling upon the receiver is proportional to

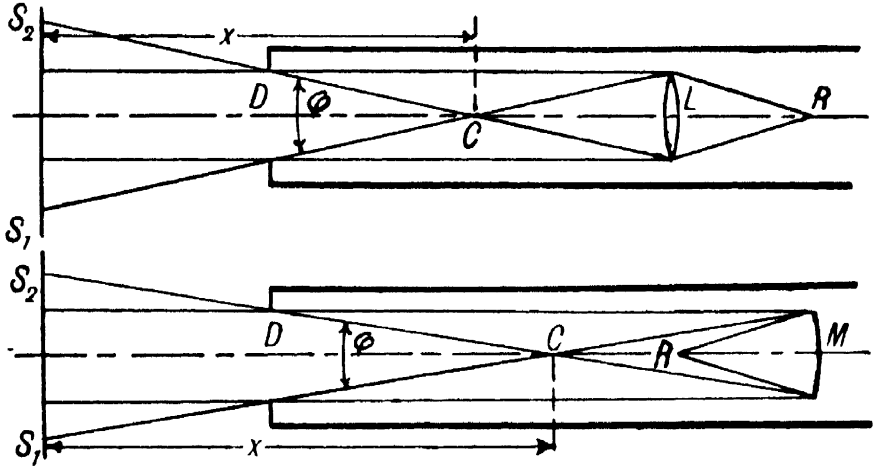


FIG. 37.—Radiation pyrometers with fixed focus.

the intensity of the radiating source. The pyrometer readings are then nearly independent of the focusing distance provided the source is of sufficient size to ensure that the image completely covers the receiver δS_2 for all conditions.

The conditions for case No. 2 are represented in Fig. 37. The diaphragm D acts as a secondary source, and the conjugate foci of the lens or mirror are situated at D and at the receiver R, the instrument therefore having a fixed focus. It is obvious from geometrical considerations that the smallest diameter of the source S_1S_2 which can be used without requiring correction of the readings of the pyrometer will be

$$S_1S_2 = \frac{x \times (\text{dia. of diaphragm D})}{DC}$$

where x is the distance from the source to the point C. The angle ϕ is usually called the angular aperture of the instrument.

The Féry radiation pyrometer shown in section in Fig. 38 represents one arrangement of the adjustable focus type of instrument made by the Cambridge Instrument Co. Ltd. The concave mirror C, made of polished rustless steel, is attached to a focusing rack so that it can be adjusted in the metal case by means of the focusing pinion F. The rays received by the mirror are reflected on to the blackened thermojunction consisting of a very small copper or silver disc to which the wires

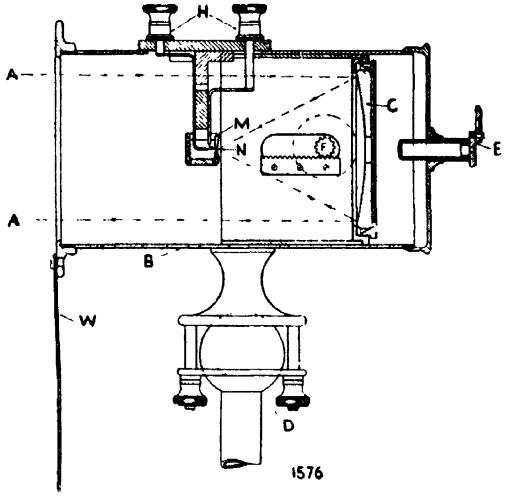


FIG. 38 —Féry radiation pyrometer.

forming the junction are soldered, and the mirror is adjusted until the focus coincides with the receiver disc.

The heating of the thermojunction induces an electro-motive force, usually measured by means of a sensitive galvanometer or millivoltmeter of high resistance connected by leads to the terminals on the pyrometer in accordance with the principles explained on p. 59, and the scale of the galvanometer may be graduated to indicate the temperature of the source. The potentiometer methods of measuring e.m.f. described on p. 70 may also be used with a corresponding increased degree of accuracy, since the readings are then practically independent of the resistances of the thermojunction, leads and galvanometer.

In order to give a clear indication when the receiver disc with its thermojunction is in the focus of the mirror C two

small semicircular mirrors M, inclined to one another, are fixed near the junction. These divide the image of the sighted object or source into two portions as indicated by the hatched parts in Fig. 39 where the central illustration shows the appearance when in focus and the other two when an adjust-

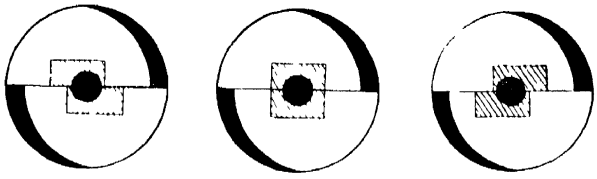


FIG. 39.—Focusing indicator on Féry radiation pyrometer.

ment of the focus is necessary. An opening of about 1·5 mm. diameter at the centre of these mirrors forms the limiting diaphragm immediately in front of the receiver disc or thermo-junction and appears as the small black circle in Fig. 39.

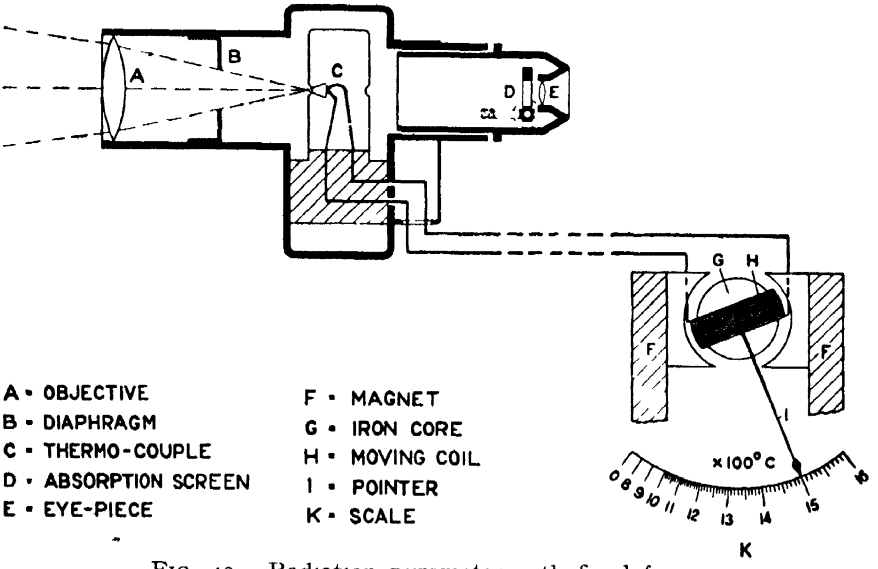


FIG. 40.—Radiation pyrometer with fixed focus.

In another heavier model more suitable for permanent installations in dusty situations a scale of distance is provided of 3 ft. and upwards with a locking screw to prevent accidental changes. The maximum distance is determined by the area of the hot object, since this distance may not exceed 2 ft. for each inch of diameter of the object. The telescope is mounted

by a hinge on heavy 1-in. steel tubing which may be clamped to a pipe fitted to the furnace wall, or to a special support.

The general type of radiation pyrometer with a fixed focus is represented in Fig. 40 connected directly to an indicator, as built by Elliott Brothers (London) Ltd. The lens A brings the rays to a focus through the diaphragm B on to a small plate of blackened platinum enclosed in the glass bulb C filled with inert gas. There are four thermocouples in series each fixed to a small plate of the blackened platinum and connected to the indicator. The instrument is sighted on to the furnace

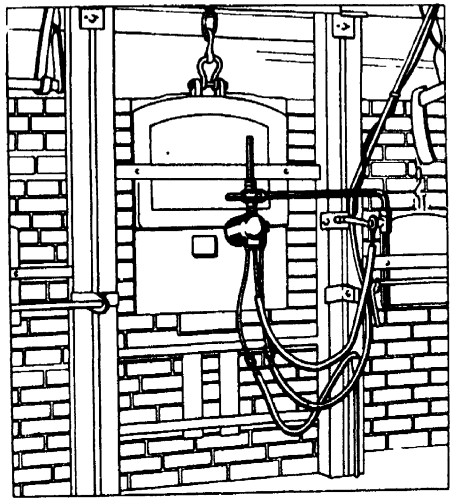


FIG. 41 —Radiation pyrometer mounted on furnace, as arranged by Elliott Bros (London) Ltd

or hot object through the eyepiece E, and an absorption screen D can be interposed by turning a milled head when the object becomes too dazzling to the eye. As long as the image of the hot object covers the thermocouples completely the distance from the lens A to the object is not important, but there is a minimum diameter of object for each distance varying from $1\frac{3}{4}$ in. at 18 in. distance to 5 in. at 6 ft. distance. In portable arrangements the pyrometer and indicator may be mounted on a movable stand. For permanent installations the casing of the instrument is provided with a jacket cooled by water or by air. The illustration in Fig. 41, due to Elliott Brothers (London) Ltd., shows this type of radiation pyrometer mounted on an adjustable arm in front of a glass furnace with the

water-cooling and cable connections. The latter may lead to the temperature indicator, recorder or controller according to the arrangement. In some installations the pyrometer may be sighted on to the closed end of a refractory tube let into the furnace, such as is shown in Fig. 35, p. 79. Most makers are prepared to supply the tube incorporated with the pyrometer

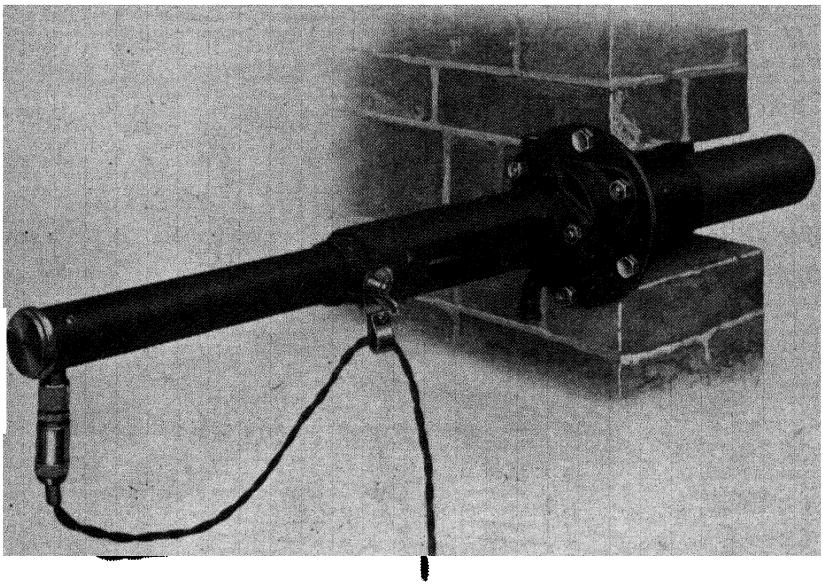


FIG. 42.—Foster radiation pyrometer mounted with sighting tube.

and one arrangement due to the Foster Instrument Co. Ltd., is shown in Fig. 42. Cooling jacket connections are provided for use if necessary. In some of these arrangements the rays are brought to a focus on the thermocouple plate by a lens and in others by means of a concave mirror.

In the Honeywell-Brown Ltd. radiation pyrometers ten thermojunctions are arranged in series as represented in the enlarged view in Fig. 43, having the hot junctions flattened in a radial form with terminal strips riveted to an annular ring of mica. The e.m.f. of the thermopile is measured by the potentiometer method, as in Fig. 30, p. 70. The radiations are brought to a focus on the flattened and blackened junctions by a suitable lens made of fused silica for temperatures of the object between 800° F. and 2300° F. (427–1260° C.) and of Pyrex for ranges 1600–3200° F. (871–1760° C.). These sub-

stances transmit most of the radiant energy within the ranges mentioned. In both ranges a narrow-angle plano-convex lens is available which is designed to sight upon a target or object not less in diameter than $\frac{1}{20}$ of the distance between the lens and the object or surface. This narrow-angle lens is used for objects of limited size or where a sighting tube is used. A wide-angle double-convex lens is also available on the higher

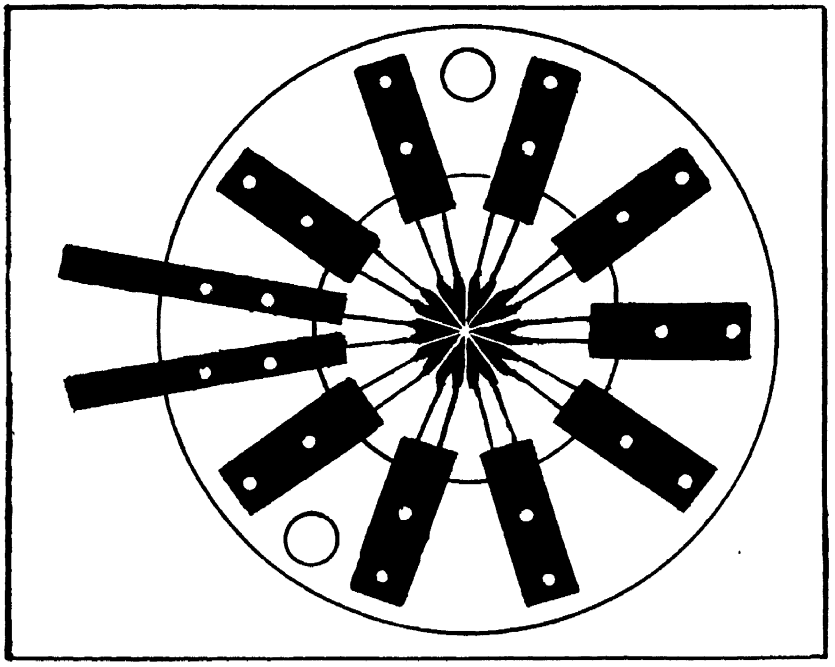


FIG 43 —Receiver of radiation pyrometer (Honeywell-Brown Ltd)

range mentioned which is capable of sighting on an object of diameter not less than $\frac{1}{7}$ of the distance between the lens and the object. A nickel compensating coil is placed in the thermocouple circuit to compensate for variations of the ambient temperature to which the instrument may be subject up to 250° F. An auxiliary lens may be mounted in the rear of the housing to facilitate the sighting on a specific object or target. These instruments are applied generally in one of the following three ways : (1) Mounted on a closed-end ceramic or metal tube ; (2) mounted on an open-ended sighting tube of these materials ; and (3) sighted directly on the object, or into a furnace through a hole in the wall. The arrangement (1)

is used only with the narrow-angle lens. The readings may be shown on an indicator or on a recorder or on both, and the instruments may be connected to a temperature controller or regulator, as described on pp. 159–169.

This firm has also developed a similar radiation pyrometer with low temperature ranges from 100° F. to 600° F. for particular use where direct contact thermometers may not be suitable for physical reasons. The lens is of calcium fluoride capable of transmitting most of the low temperature radiations. A resistance winding and a heating element are incorporated to control the internal temperature at 125° F. to avoid disturbances due to varying ambient temperatures. The resistance winding forms one leg of an a.c. bridge, and any unbalance due

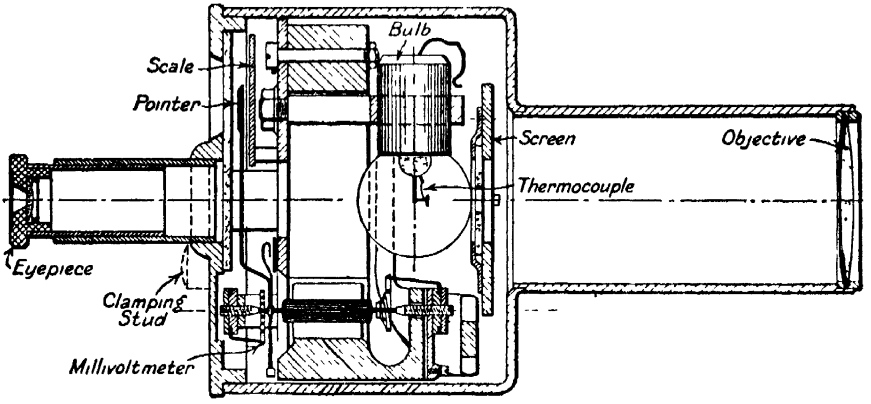


FIG 44 —Radiation pyrometer with indicator in view

to a change of this internal temperature acts through a single stage of electronic amplification on the control grid of a thyratron tube or valve, which then suitably alters the current passing through the heater element to keep the internal temperature nearly constant at the required value.

The sectional view in Fig. 44 represents the fixed focus radiation pyrometer developed by The Pyrometer Instrument Co., Inc., N.J., U.S.A., where the indicator or millivoltmeter is situated in the instrument immediately in view over the eyepiece. The objective lens is of quartz about 45 mm. diameter, and concentrates sufficient radiant energy on the thermocouple or thermopile enclosed in the bulb. The reading is obtained when the press button or clamping stud is depressed, and the release of the stud while pointing the pyrometer at the object clamps

the needle. A second depression releases the needle for the next reading. Sliding adjustment of the eyepiece brings the object or hot body clearly into view. While the instrument operates independently of distance over rather wide limits, under general conditions the distance between the objective lens and the furnace sight hole should not exceed 15 times the diameter of the sight hole, but not closer than 20 in., and the sight hole should not be less than 2 in. diameter for correct readings.

In the open hearth steel furnace the charge of steel on the hearth receives heat from the hot gases and the furnace walls mainly by radiation. The surface of the molten metal becomes covered with a layer of slag. Therefore the heat has finally to reach the molten metal through this slag and the metal has a lower temperature than the surface of the slag. When the gases, furnace walls and surface of the slag may have an average temperature of, say, 1700–1750° C. (3092–3182° F.) the average temperature of the molten metal may be, say, 1525–1575° C. (2777–2867° F.). These remarks may not apply when large quantities of air or oxygen are blown into the molten metal during the process of heating. It is not an easy matter to measure the temperature of the metal under furnace conditions and it is perhaps usually inferred from that of the furnace as measured by the radiation or optical pyrometer sighted on the furnace roof or on the surface of the slag. Estimates of the pouring temperature of the steel are sometimes made by sighting the pyrometer on to the stream of metal or on the surface of the metal in the ladle. There are some difficulties in this method due mainly to uncertainties of the emissivity values under these conditions, which are discussed later on p. 105. It certainly would seem to be more satisfactory to be able to measure the temperature of the metal before it is poured. Under some conditions it may be possible to insert a closed refractory tube into the body of metal and sight the pyrometer on to the closed end in the metal, but under these temperature conditions the life of such a tube would probably be short.

Messrs. Leeds and Northrup Co. have developed a special arrangement of radiation pyrometer and immersion unit or tube which is inserted through the wicket hole and downwards

through the layer of slag into the body of molten metal. This immersion "Rayotube" pyrometer consists basically of a steel tube open at the bottom end with the enclosed radiation pyrometer sighted on the metal at or through this orifice. At the top end of the tube is a hand wheel to facilitate easy handling, and this wheel also contains the necessary connections. The operator inserts the assembly into the bath for a few seconds and pushes a plunger switch enclosed in the hand wheel. A stream of cold clean air under pressure flows down the tube to keep it clear of molten metal and slag, and the paper drive mechanism in the recorder starts the chart travelling and the inking pen crosses the chart to record the bath temperature. This pen mechanism is operated automatically on the potentiometer principle described on pp. 73 and 154. In skilled hands the operation takes only 30 seconds with the actual time of immersion 5 seconds. The recorder is designed to keep successive records spaced for easy reading and runs ½ in. after each measurement, and then stops automatically. To check the recorder action at any time the operator can press an external switch, and when the same switch is turned the instrument standardises itself automatically. The recorder is provided with a sliding window so that the operator can make notations on the chart. To illumine the recorder scale and chart, and to show the operator that the recorder is "on" when he is ready to immerse the pyrometer unit, there is a fluorescent lamp inside the case door. As the operator withdraws the unit from the molten metal he scrapes off any loosely adhering slag or steel on the edge of the wicket hole, and places the unit on the floor to cool. The optical parts of the instrument are shielded from metal splashes by a protecting window which is easily replaced if damaged. For the occasional internal cleaning and inspection the unit can be taken apart quickly. It may be desirable to check the calibration of the unit occasionally and a checking unit is available consisting of a radiation pyrometer at one end and a galvanometer at the other. It can be clamped and connected to the ordinary unit and the two together sighted on a common part of the furnace. The galvanometer reading gives the necessary check on the recorder and if the latter is in error the operator turns a dial until the recorder reading becomes standardised.

Errors of Radiation Pyrometers.—The principal sources of error in radiation pyrometers may be enumerated as follows :

The influence of lag, or time required to obtain a constant reading. The effect of distance between the pyrometer and radiator and of the size of the image. The effect of dirt or dust on the " optical " system. Lack of " black body conditions " of the radiator and receiver and the influence of the temperature of the receiver.

On exposing a radiation pyrometer to the radiations from a source at constant temperature, the indications of the pyrometer show a time lag while the instrument is heating up. A condition of equilibrium will be reached when the receiver loses by conduction, convection, and radiation as much heat as it receives. Different pyrometers, even of the same make, seem to exhibit different times of lag, and to keep this time lag small the heat capacity of the receiver should be reduced to a minimum, and also the thermocouple wires should be as small in diameter as possible, consistent with mechanical strength, in order to prevent excessive conduction of heat along the wires.

In recent years careful attention to design has reduced the time lag between exposure to the temperature and its record on the recorder. Messrs. Leeds and Northrup have one design of radiation pyrometer and recorder where the action is so rapid that normal variations in temperature along the length of a hot object are recorded in 1·5 seconds or less.

It was seen on p. 83 from the simple geometrical considerations of the optical systems that the readings of a radiation pyrometer theoretically should be independent of the focusing distance from the pyrometer to the radiator or source, and also independent of the size of the radiator or object and image, provided the object is of sufficient size for the aperture of the instrument. Actually this simple condition is hardly ever fulfilled because of atmospheric absorption, and imperfections of the instrument. The error due to atmospheric absorption is likely to be very small unless fumes or fog intervene between the sighted object and the instrument. The imperfections of the instrument include such factors as the varying absorption of the lens or mirror, and the increase of the temperature of the pyrometer by radiation and convection

as the instrument is brought nearer to the source, unless it is specially cooled.

The ordinary calibration of radiation pyrometers is usually made with the mirrors or lens quite clean. In industrial practice the lens or condensing mirror is liable to get coated with dirt or dust and then the instrument may read too low. Examples were given on p. 81 showing the influence of a radiator which does not fulfil black body conditions. Although the inside surface of the pyrometer case is thoroughly blackened to minimise the reflection of stray rays, some reflection may occur, and it may be better to have a fine screw thread on the inside surface of the case to disperse the reflections. The temperature of the receiver and the thermojunction increases with the amount of energy absorbed, that is, with the temperature of the source. According to Messrs. Burgess and Foote* the temperature of the receiver may be about 200° C. when the pyrometer is sighted on a source at 1500° C. for the average run of Féry pyrometers, though it varies greatly with different pyrometers.

It is sometimes assumed that the Stefan-Boltzmann law, $R \propto (T^4 - T_0^4)$, applies without modification to radiation pyrometers, where R is the energy absorbed by the receiver, T the absolute temperature of the source, and T_0 the absolute temperature of the receiver, and that this law may be used to extend the scale of temperatures beyond the calibrated range. Owing to the various instrumental imperfections, however, the law only applies approximately, and instead of the index 4, experiment shows the more general relation is given empirically by,

$$R = a(T^b - T_0^b).$$

Thus, $$\log R = \log a + b\left[\log T - \frac{0{\cdot}4343}{b}\left\{\left(\frac{T_0}{T}\right)^b + \ldots\right\}\right].$$

If $$\frac{-0{\cdot}4343}{b}\left(\frac{T_0}{T}\right)^b = q,$$

Then, $$\log R = \log a + b(\log T + q) \text{ nearly.}$$

Since the quantity q is only small and b is not far from the value 4, it may be assumed that

$$q = -\frac{0{\cdot}4343}{4}\left(\frac{T_0}{T}\right)^4.$$

Therefore, to find the value of b from a set of experimental observations, the logarithm of R and (log T+q) are plotted on graph paper, when b is given by the gradient of the line.

Messrs. Burgess and Foote * have experimentally determined b for several radiation pyrometers. With 22 different Féry pyrometers b had values ranging from 3·28 to 4·26, the average for the 22 instruments being about 3·89.

A radiation pyrometer may be calibrated up to, say, 1400° C. by comparison with the platinum resistance or thermoelectric pyrometers and the law of radiation for the instrument deduced up to that temperature. While the law might be assumed to hold with a fair degree of accuracy for a few hundred degrees beyond this point, obviously it should not be carried too far beyond the limits of direct comparison.

Optical Pyrometers.—Optical pyrometers are arranged to make use of the luminous radiations only. In the usual construction of this type of instrument the intensity of the light radiated from the sighted object is compared or matched with that from some standard source, and the main difference between the various instruments lies in the methods by which the comparison is made.

It is not the usual practice to attempt to measure the intensity of the whole of the luminous radiations for the reason that the sensitiveness of the eyes varies for different persons viewing full luminous radiations, and it is found to be more accurate to compare the radiations of some definite wavelength, that is, monochromatic light. The temperatures indicated by an instrument calibrated under black body conditions are known as "black body temperatures," and when the instrument is sighted on a body which is in the open and does not fulfil black body conditions the apparent temperature will be lower than the true temperature as was explained on p. 81. Therefore, to ascertain the true temperatures of such bodies it is necessary to know the relations between the apparent and the true temperatures by direct experiment under the particular conditions in which the hot body is exposed. If there should happen to be large differences of temperature in the neighbourhood of the sighted body reflection from the surface of the object may also affect the apparent temperature.

* *Characteristics of Radiation Pyrometers*, Bureau of Standards, U.S.A.

Under certain conditions some substances are luminescent; for instance, the ordinary gas mantle which has been saturated with salts becomes luminescent at high temperatures. For such cases the ordinary laws of radiation may not apply.

Laws of Radiant Energy.—When the radiations from a black body are dispersed by a suitable prism, it is found that some particular wave-length gives a maximum intensity of radiant energy. The displacement laws of Wien give expression to the relationship as follows.

$$\lambda_m T = C_1 \quad . \quad . \quad . \quad . \quad (6)$$

$$I_m = C_2 T^{-5} \quad . \quad . \quad . \quad . \quad (7)$$

where C_1 and C_2 are constants, λ_m is the wave-length of maximum radiant energy, T is the absolute temperature of the black body, and I_m the maximum intensity of the radiant energy.

Lummer and Pringsheim found C_1 to have an average value of 2940 for black body radiations where λ_m is expressed in the number of thousandths of a millimetre and T in deg. Cent. abs.

Wien also proposed the following expression for the intensity of the black body radiations I at any wave-length λ.

$$I = \beta \lambda^{-5} \varepsilon^{\frac{-\beta_1}{\lambda T}} \quad . \quad . \quad . \quad . \quad (8)$$

where β and β_1 are constants and ε the base of natural logarithms 2·7183.

To make this expression fit more accurately the results of experiments Planck proposed the modification

$$I = \beta \lambda^{-5} \varepsilon^{\frac{-\beta_1}{\lambda T}} \left(\frac{I}{I - \varepsilon^{\frac{-\beta_1}{\lambda T}}} \right) \quad . \quad . \quad . \quad (9)$$

This expression forms the basis of the definition of the temperature t above the gold point on p. 245. Within the visible portion of the spectrum, that is, between 0·8 μ and 0·4 μ, where μ=0·001 mm. or 1 micron, the value in the brackets in eqn. 9 is nearly unity. If I_1 and I are the intensities at the two absolute temperatures T_1 and T, then, on taking logarithms for eqn. 8,

$$\log_e \frac{I_1}{I} = \frac{\beta_1}{\lambda} \left(\frac{1}{T} - \frac{1}{T_1} \right) \quad . \quad . \quad . \quad (10)$$

If T_1 and T are in deg. Cent. abs. then $\beta_1 = 14{,}380$ with λ measured in terms of the unit micron.

Thus, if I and T refer to black body radiation and I_1 and T_1 to the measured black body values for a "grey" or "selective" body at the true temperature T, and for the same wave-length, then, by definition, the relative emissivity $E_0 = \frac{I_1}{I}$

It should be understood that the relation between I_1 and T may not obey Wien's laws because these laws apply to black body conditions. The wave-length 0·65 microns (monochromatic red light) is commonly used in optical pyrometers, and, in this case,

$$\log_{10} E_0 = \log_{10} \frac{I_1}{I} = 9570 \times \left(\frac{1}{T} - \frac{1}{T_1} \right) \quad . \quad . \quad (11)$$

The accompanying table gives a selection of values for true temperatures against the observed black body temperatures, taken from *Pyrometric Practice.**

READINGS OF OPTICAL PYROMETER SIGHTED IN OPEN

Black body observed temperature	True temperatures and values of E_0											
	Molten copper.		Molten iron		Solid iron oxide		Solid nickel oxide		Molten slag		Bright platinum	
°C	°C	E_0	°C	E_0	°C	E_0	°C	E_0	°C	E_0	°C	E_0
1000	1150	0·16	—	—	1004	0·96	1007	0·92	—	—	1087	0·32
1200	1405	0·16	1296	0·4	1210	0·90	1215	0·86	—	—	1320	0·32
1400	—	—	1525	0·4	—	—	—	—	1455	0·65	1555	0·31
1600	—	—	1758	0·4	—	—	—	—	1670	0·65	—	—
1750	—	—	1935	0·4	—	—	—	—	1830	0·65	—	—

Le Chatelier in 1892 seems to have been the first experimenter to design and use an optical pyrometer successfully. An expanding or iris diaphragm was used to alter the amount of light entering the instrument. In this case the intensity of the light would vary as the square of the diameter of opening and a calibration at two known temperatures was sufficient to connect the temperatures with the diameter of the opening of the diaphragm. A modification of the Le Chatelier instru-

* Technologic Paper No. 170, U.S. Bureau of Standards, by Foote, Fairchild and Harrison.

ment was introduced by Féry, where a pair of glass absorbing wedges were placed in front of the objective of the telescope and could be moved laterally by means of a screw until the light from the object under observation was made photometrically equal to that emitted by a standard lamp. These pyrometers, however, are not now considered to be as accurate or as convenient as other instruments more recently developed.

Wanner Optical Pyrometer.—In this type of instrument the monochromatic rays of light from the object and from a standard lamp are produced spectroscopically and are therefore truly monochromatic. The comparison of the brightness is obtained by means of a polarising device. The arrangement is represented in Fig. 45. Diffused light from a standard 4-volt electric lamp passes through the slit S_1 and from the object through the slit S_2. The two beams are rendered parallel by the lens L_1 which is placed at a distance equal to its focal length from the slits, and are then each dispersed into

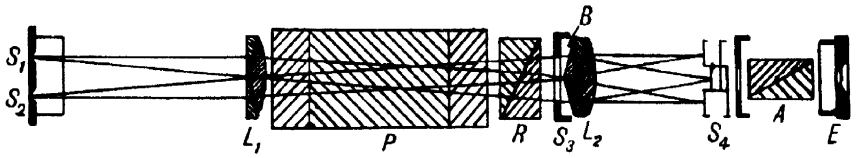


FIG 45.—Wanner optical pyrometer arrangement

a continuous spectrum by the direct-vision prism P. The polarising prism R next separates each of these beams into two beams polarised in planes at right angles. Various substances are capable of polarising the light passing through them, i.e. instead of the issuing light consisting of waves in all directions, two beams are produced, each consisting of waves in a single plane only, and the two planes are at right angles. The lens L_2 would therefore form four images and the bi-prism B in contact with the lens L_2 is made so that two fields of red light, polarised in planes at right angles, are focused on the slit S_4, one coming from the slit S_1 and the other from S_2. All the other images are cut off at the slit S_4. These two beams of red light enter the Nicol analyser A and the observer looks through the eyepiece E to ascertain when the two beams are of equal intensity. This can be obtained by rotating the analyser A, and the angular position

of the analyser is then a measure of the temperature of the object. The analyser is simply another polarising prism. In a particular angular position of the analyser polarised light would be cut off completely; in another position at right angles to this the maximum amount would pass through. For an intermediate angular position only a component of the polarised light could pass through. If the intensities of the light from S_1 and S_2 were equal, and the analyser set at an angle of 45° with the plane of polarisation of each beam, the eye would see a single circular red field of uniform brightness. If one slit then received more light than the other the corresponding field would brighten, but the two fields could be brought back to equality again by rotating the analyser in the proper direction, thereby cutting off more light from the brighter field and admitting more from the darker. The angle of rotation of the analyser indicates the temperature of the object to some scale. Thus, if θ is the angle turned through to bring the two fields to equal brightness, and I_1 and I_2 the intensities of the light through S_1 and S_2, then,

$$\frac{I_1}{I_2} = \tan^2 \theta.$$

For purposes of calibration a standard amyl-acetate lamp is provided on which the instrument can be sighted and the current passing through the electric lamp is adjusted so that equal brightness is obtained from the two lamps with the analyser set at the "normal" or "zero" point. The height of the flame needs to be carefully adjusted to the gauge provided and should burn about ten minutes before readings are taken.

The apparent temperature of the standard lamp may be taken to be 1673° C. absolute, and thus the apparent black body temperature of the sighted object is calculable from Wien's equations on p. 96. In the industrial form of this instrument the standardisation has been further simplified and made direct reading by having a second scale on the analyser graduated in temperatures.

For work of precision a rheostat and milliammeter should be inserted in series with the battery and electric lamp so that the current through the lamp can be maintained constant.

Otherwise the slightly changing voltage of the battery with the period of operation may affect the accuracy of the results. A disadvantage of this type of instrument is the difficulty of sighting the instrument exactly on the spot desired Also the absorption of light which takes place through the large number of prisms and lenses renders it almost useless for temperatures below, say, about 800° C. (1472° F)

Instruments using polarising apparatus are liable to error if the object sighted on emits polarised light When an incandescent object is viewed at right angles to its surface the amount of polarised light is usually small, but when viewed at an acute angle the amount of polarised light in this direction may be appreciable This source of error may be eliminated by taking the mean of four readings for azimuths 90° apart, but obviously this would be troublesome in practice For many substances, however, such as iron and porcelain, the emission of polarised light is practically negligible

Holborn-Kurlbaum Type of Optical Pyrometer. -This type of instrument is usually referred to as the " disappearing filament " optical pyrometer It measures the temperature by comparing the brightness or intensity of the light from the observed object with that from the filament of an electric bulb under standardised conditions The filament appears against the background of the sighted object if the brightness of one is different from that of the other and the filament current is altered until the filament disappears in the view, when the temperature is deduced from the current passing One arrangement is represented diagrammatically in Fig 46 A small 2- or 4-volt lamp L is mounted so as to lie in the focal plane of the objective lens by use of the focusing screw S The lamp circuit in this arrangement is completed through the battery, rheostat and milliammeter which is usually graduated in terms of temperature. The stops or baffles D are intended to stop extraneous reflections from disturbing the comparison of brightness Some makers prefer to arrange the resistance of the lamp circuit into one arm of a Wheatstone bridge with the indicator connected across the bridge in the way shown in Fig 17, p 47 The lamp and bridge are usually arranged in a compact unit replacable by another unit without needing to be recalibrated. With this system the indicator reading may

be arranged at any convenient starting point by balancing the bridge at this filament circuit resistance. Leeds and Northrup Co. use the potentiometer method referred to on p. 47, with the advantage that the readings are independent of the accuracy of the galvanometer or indicator or the lengths of the leads. The indicator may be arranged to have more than one scale or range, and the different scales can be brought into action by the interposition of absorption glasses in the higher ranges. Temperature readings higher than 2000° C. are rarely

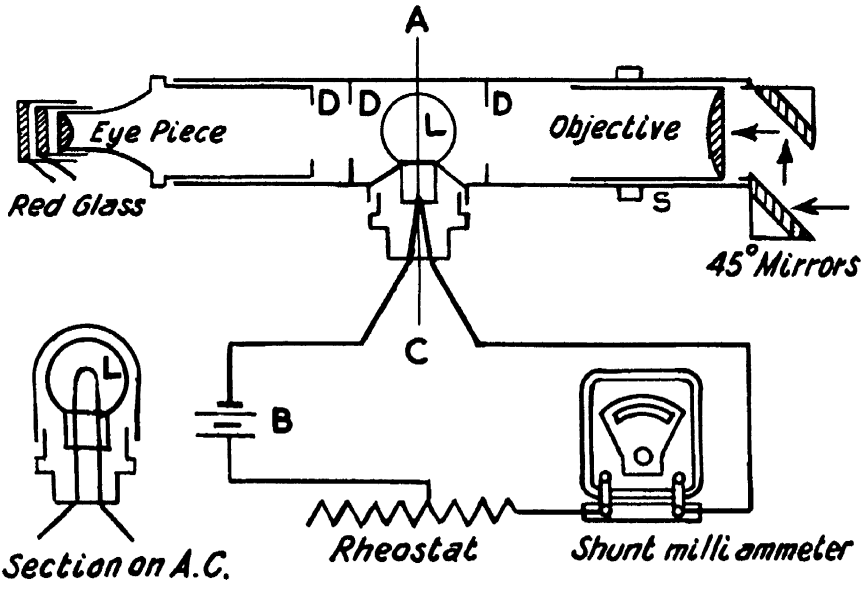


FIG. 46 —Holborn-Kurlbaum optical pyrometer

required in industry, but in special cases approximate measurements are practicable up to 4000° C. say. Optical pyrometers cannot be readily used as the sensitive element for the operation of recorders or temperature controllers.

At high temperatures the brightness of the image may be too intense for the observer's eyes, but the introduction of monochromatic red glasses before the eyepiece enables readings to be obtained. Below about 800° C. (1472° F.) the red glasses are not usually necessary, that is, down to the limit of the instrument, say, 600° C. (1112° F.). Two red glasses are usually required for temperatures above 1200° C. (2192° F.), and above 1500° C. (2732° F.) it may be necessary to bring absorbing

glasses into action, or the double-prism mirror shown in Fig. 46 before the objective, which, of course, require calibration before use. With care the precision obtainable with this pyrometer is good, say $\pm 5^\circ$ C., and different observers do not differ appreciably in their readings. The relation between the current C and the temperature t for the lamp is in general accurately enough expressed by a formula of the type,

$$C = a + bt + ct^2$$

where a, b and c are constants for the particular lamp. If the lamp has been aged or burned for some time at a temperature higher than that obtained in ordinary use the current and temperature relation should not change appreciably after several years' use, but if not aged in this manner considerable changes may result in course of time and errors thereby be introduced.

Some makers incorporate a dry battery and the indicator in the same casing containing the telescopic arrangements. In the optical pyrometer built by The Pyrometer Instrument Co. the brightness of the red rays transmitted through a colour filter is compared with the constant brightness of a bulb filament supplied from the enclosed dry battery through an adjustable rheostat. The light emitted by the hot body or object is passed through an adjustable circular optical wedge of varying density on which is the scale of temperature of the hot body. A testing ammeter is also incorporated for the adjustment of the lamp current to the required value. When the master lamp which is provided is inserted and the current is adjusted to the value stated on the lamp the instrument is sighted on a hot body of constant temperature. The service lamp is then inserted and the current adjusted to give the same reading of temperature.

Other makers place an accumulator in a leather case slung from the shoulder. Messrs. Leeds and Northrup Co. enclose the batteries and the potentiometer with the temperature scales and galvanometer in a strong casing of light-weight alloy supported in front of the operator by means of straps over the shoulders and back. The telescope is also a light casting with a rubber shield in front to exclude extraneous reflections, and when not in use it is carried in a clip on the side

of the potentiometer casing. This leaves the operator's hands free to record the readings and thus renders it easy to use the pyrometer when a series of readings are required. The filament circuit is closed when the telescope is gripped in the hand. To keep out dust from the potentiometer the front of the casing fits tightly against a gasket. A breather hole permits the air inside to expand and contract; and air entering this hole passes over a small magnet which removes magnetic particles, and then through a filter to catch dust.

The illustration in Fig. 47 shows this pyrometer in use.

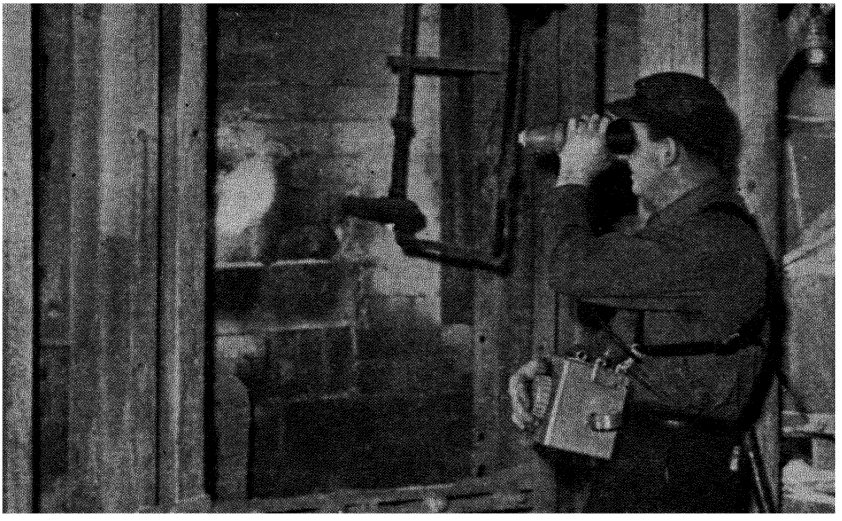


FIG 47 —Leeds and Northrup optical pyrometer in use.

The operator is adjusting the brightness of the lamp filament by turning the large knob on the potentiometer which at the same time roughly adjusts the temperature scale. A smaller knob below is then pushed in and turned until the galvanometer in front of the temperature scale reaches the point of balance. This knob at the same time brings the temperature scale to the correct setting.

In a special design for the measurement of the temperature of molten cast iron the pyrometer telescope assembly is mounted on a 6-ft. tube with the immersion end closed by a special heat-conductive tip. The operator plunges the immersion tip into the molten iron and obtains a reading in the

usual way. The main advantage of this arrangement is that it gives true temperatures independent of surface emissivity.

Attempts have been made to estimate high temperatures by comparing the colour of the heated object with standard colours. The method is not generally considered to be sufficiently reliable in practice because the eyes of different persons seem to respond differently to comparisons of colour. Messrs. Bowen Instrument Co., Ltd. make a simple pyrometer on the colour basis under the trade name "Pyrokolor." The hot object is sighted through a slot in a cursor which is moved over a temperature scale. If the reading is too low the object appears to be green in colour and if too high the object appears to be red. When the cursor is set correctly the appearance is "white." The makers state that on first using this instrument the error may be 50° C. but with experience the error may be not greater than ± 10° C. to ± 20° C.

Errors and Corrections in Optical Pyrometers.—In the Wanner type of instrument both the light from the standard lamp and that from the hot body are analysed by spectroscopic means and a practically monochromatic band in the red is selected for comparison. In the other types the red light is obtained by means of red absorption glasses, and one objection to these glasses is that the light may not be truly monochromatic. This may cause some errors as is signified by the relation $\lambda_m T = \text{constant}$. The hot body is not at a constant temperature, whereas that of the standard source in the Wanner type of instrument is practically constant. This introduces small variations and affects the adjustment of the two fields of light to equality. The error involved may be of the order ±10° C. at 1500°C. if not allowed for in the calibration of the instrument.

The adjustment of the current through the standard lamp, usually an electric filament, is commonly obtained by means of a rheostat. The steps in the rheostat should not introduce changes in the temperature by more than 5° C. at each step, as obviously the accuracy of the comparsion is practically limited to the change of temperature at each step.

Optical pyrometers have come into extended use in steel works in recent years for measuring furnace temperatures, the pouring temperatures of liquid steel, and steel temperatures

during re-heating, forging, rolling and annealing. Their chief merit lies in the absence of serious time lag, the ease with which they can be operated, and the knowledge available of the emissivities of iron and iron oxide for the wave-lengths used, but they are subject to errors or corrections according to the conditions under which they are used. Being calibrated for black body conditions, the optical pyrometer sighted into a furnace of *uniform* temperature should give the true temperature. The temperature of a furnace, however, is rarely quite uniform, and some reflection may occur from a body of metal in the furnace having a lower temperature than the walls or flames. In that case also radiations may be emitted by the flames coming between the metal sighted on and the instrument. As mentioned previously, in the open hearth furnace the temperature of the molten steel on the hearth may be below that of the furnace itself, because the heat has to travel through the layer of slag on the top of the metal. To obtain the temperature of the steel before being poured it would seem to be best to sight the pyrometer on to the bottom of a refractory tube well immersed in the steel.

As in the radiation pyrometers, when the optical pyrometer is sighted on a body in the open the conditions may be far removed from the black body conditions for which the instrument is usually calibrated. When estimating the temperature of steel in the open the problem is further complicated by the coating of oxide which may be formed on the surface, the oxide having a higher emissivity than the metal; but the oxide is a poor conductor of heat and therefore the surface of the oxide during cooling in the open is at a lower temperature than that of the metal underneath. This feature was discussed previously on p. 81.

The degree of accuracy in the calibration of radiation and optical pyrometers may depend to some extent upon the type of instrument and on the methods adopted. Under favourable conditions the accuracy of calibration of radiation pyrometers may be of the order $\pm$ 10° C. up to about 1300° C. and of optical pyrometers $\pm$ 1% of the temperature readings up to 1300° C. (2372° F.) with rather wider limits for higher temperatures.

Standardised tungsten strip lamps are available to check

the readings of optical pyrometers and are usually calibrated for current in terms of temperature. Before calibration such a test lamp should first be tried for constancy by comparing a reading before and after a period of burning the lamp at a temperature not less than the highest test temperature.

Photo-electric cells are becoming of increasing importance in the detection or measurement of temperatures as is illustrated by Fig. 34, p. 75 and Fig. 51, p. 111. The name refers to devices where incident radiations, usually luminous, cause an emission of electrons from what is called an "activated surface." In further explanation it may be said that, according to modern ideas of atomic structure, an atom is possessed of a central core of relatively heavy particles, some of which carry or constitute positive charges of electricity. Round this central core circulate electrons in various orbits, where each electron carries or constitutes a negative charge. Normally the positive and negative charges in the atom neutralise one another, but in certain cases some of the electrons describing outer orbits can be caused to leave the atom if sufficient energy is supplied, without altering the nature of the atom, but the atom becomes a "positive ion" because it is left with more positive than negative charges. In that condition it will attract electrons to become a neutral atom again. Similarly, if a neutral atom acquires an extra electron the atom becomes a "negative ion" and it will then tend to repel electrons, and it may readily part with the extra electron it has acquired. The flow of free electrons from one place to another is taken to constitute a current of conductive electricity. This flow is opposite from the conventional + and − signs usually marked on batteries, that is, the flow of elec-

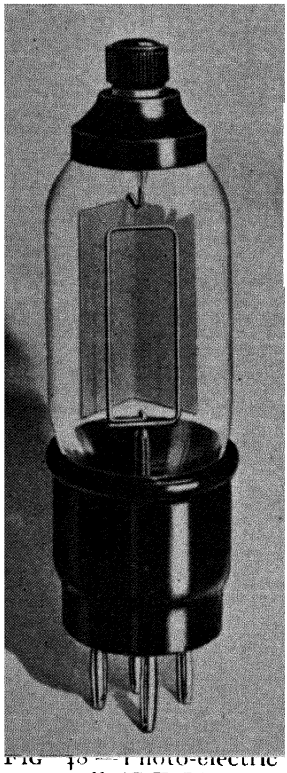


FIG. 48.—Photo-electric cell (G E C.).

trons enters the + end of a battery and leaves at the − end. When energy is absorbed or developed at a surface some of the free electrons at or near the surface may acquire enough kinetic energy to enable them to leave the surface atoms. Most of the substances which are sensitive in this respect respond to light waves or near infra-red, although X-rays, which have very short wave-lengths, are capable of causing some emission of electrons from almost any substance. Energy may also be transmitted to the surface by internal heating as in the heated cathode of ordinary thermionic valves. Some secondary emissions of electrons may also take place where moving electrons happen to come into contact with other atoms, and by the impact also of moving ions.

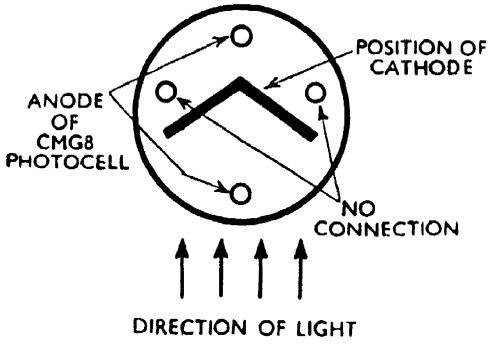


FIG. 49.—Base of photo-electric cell.

The elements which give relatively high photo-electric sensitivities in the visible spectrum are cæsium, potassium, rhubidium and sodium. Cæsium is the element commonly used as the cathode or emitting surface deposited as a layer of molecular thickness on a surface of silver oxide, antimony or bismuth, and mounted in a glass bulb having either almost a complete vacuum or an inert gas such as argon at a suitable pressure. The cathode is usually formed as a semicircular or V-shaped plate in the middle of the bulb. The anode or receiver of electrons may be a rectangular wire grid on a glass pinch in front of the cathode. The general appearance of one arrangement made by The General Electric Co. Ltd. is shown in Fig. 48 while Fig. 49 shows the underside view of the base. The four pins have the standard spacing to give the correct plugged position of the cell. The vacuum type is the simplest

form of cell and the current produced under a given illumination increases as the anode potential is raised to about 20 volts. Under this latter condition the current obtained from the bulb is nearly proportional to the total illumination of the cathode and is called the primary electron emission. A higher current is obtainable from gas filled cells due to the gain of secondary emission on applying a higher voltage to the anode. With a low anode potential the velocity of the electrons from the cathode is correspondingly low and in their passage to the anode they collide with and rebound from some of the gas molecules. At higher anode voltages the velocities of the primary electrons are greater and may be so disruptive as to knock out one or more electrons from some of the gas atoms, leaving behind a positive gas ion in each case. These secondary electrons so produced join in the emission and may in turn produce further emissions and the effect thus becomes cumulative. At the same time some of the ions and electrons may recombine and neutralise the ionisation process. The ratio of the photo-electric current to the primary current or emission is termed the gas factor or magnification and normally may be about 8. If the anode voltage were made high enough some of the gas ions produced may be driven on to the cathode and due to their large mass may produce further electron emissions from the cathode. This action, however, might continue after light is cut off from the cathode and may result in a glow discharge similar to that in a cold cathode tube, and it then has ceased to be a photo-cell; in fact, if allowed to continue for any length of time the light sensitiveness of the cathode may be destroyed. The gas filled cell is therefore more sensitive but less stable than the vacuum cell. The latter cell is also very rapid in action, there being no measurable time lag between the impingement of the ray of light on the cathode and the photo-electric current produced. The gas filled cell, although rapid enough for many purposes, has a measurable time lag which may interfere with the true response when the signal impulse is very short or varies rapidly in intensity.

Vacuum cells with secondary emission magnification equal to that of a gas filled cell are available but are more costly to install. There are two cathodes, one primary and the other secondary. The primary cathode is usually deposited on the

inside of the bulb, while the secondary or target has a central position and is surrounded by the anode or collector. The secondary cathode is given a lower voltage than the anode.

A thin deposit of cæsium is commonly used as part of the photo-electric element and has different sensitivities according to the substance or element on which it is deposited, and in all cases it is selective in response to different wave-lengths. The cæsium-silver oxide cell is more sensitive in the near infra-red or heat region, say from 1×10^{-3} mm. to $0{\cdot}55 \times 10^{-3}$ mm., than in the visible spectrum. The cæsium-antimony cell is very sensitive within the visible spectrum, say from the wave-lengths of about $0{\cdot}7 \times 10^{-3}$ mm., the red end, to $0{\cdot}4 \times 10^{-3}$ mm., the violet end, and has little response to heat waves. The cæsium-bismuth cell seems to lie between the other two both in respect to sensitivity and wave-lengths. Other deposits, such as potassium on silver oxide in a vacuum cell, give a response throughout the visible spectrum, while the sodium gas filled cell responds to ultra-violet rays between 0·4 and $0{\cdot}3 \times 10^{-3}$ mm. wave-lengths, and the cadmium gas filled cell between 0·3 and $0{\cdot}25 \times 10^{-3}$ mm. Tantalum, thorium and titanium cells have similar ranges in the ultra-violet region.

The photo-electric current obtained from these emission cells is always very small, rarely more than a few microamperes from a primary emission photo-cell, and often less. This current has to be amplified for use in industrial measurements of temperature and is usually carried out in the same way as in radio sets by feeding the current to the grid of a thermionic valve. One such arrangement is described on p. 75 in relation to a modified potentiometer and shown in Fig. 34. In some arrangements the amplified current may be used to operate a relay for purposes of control.

Another method of amplification may be obtained by repeating in successive stages the process of secondary emission described previously on p. 108. These systems are usually called "electron multipliers." The progressive emission has to be directed on to the several secondary cathodes in series and various methods are used to give the required direction, but a description of these would lie rather outside the scope

of the present work. For further information the reader may consult a standard publication * on the subject.

Another form of photo-electric cell is commonly termed the *rectifier* cell and is sometimes referred to as *barrier layer, blocking layer* or *self-generative* cell. The term "rectifier" cell comes from the property of allowing electrons to pass from one surface to the other more readily in one direction than in the other direction. In the usual construction a semi-conductor is supported on a metal plate to give mechanical strength. A thin layer of metal, say gold or platinum, is deposited on the surface of the semi-conductor by sputtering or vapour condensation, and so thin as to pass some of the light falling on it to the semi-conductor. One arrangement of this type of cell made by The General Electric Co. Ltd. is shown mounted in Fig. 50. When incident light falls on the central part an equivalent current can be produced in an external circuit connected to the two pins shown. Cells of this type require no external source of potential and are usually adopted to measure or to indicate illumination on a dial instrument to give direct readings, as in exposure meters, foot candle meters, etc., though they have been used to measure temperatures.† For a given illumination a higher current is produced than in the primary emission cell, perhaps a few hundred microamperes in place of a few microamperes only, and their sensitivity to waves of light agrees more nearly with the visual range. The ordinary rectifier cell is of low resistance and is primarily a source of current than of potential. Therefore this cell may not be suitable for use with valve amplifiers, though capable of operating a delicate relay. In recent years, however, rectifier cells of high resistance have been produced capable of acting

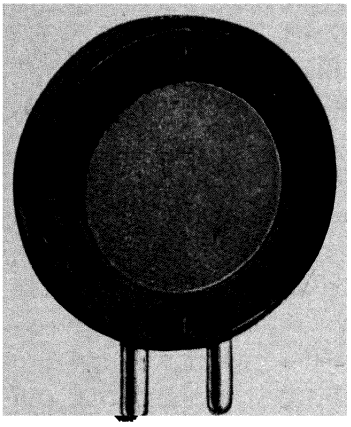


FIG 50.—Rectifier cell (G E C)

* *Photo Electric Cells in Industry*, by R. C. Walker (Pitman).

† "Barrier-Layer Photo-Electric Cells for Temperature Measurement," by T. Land, *J. Iron and Steel Inst.*, Vol. 149.

as voltage generators to operate heavier relays through valve amplifiers. The cells are used generally for many purposes in industry outside the scope of this work and for further information reference may be made to the book mentioned on p. 110.

Photo-conductive cells made from some substances such as metallic selenium, lead sulphide, etc., when specially prepared are capable of altering their electrical conductance or resistance when subject to incident waves of light. Selenium may be nearly non-conductive in the dark but on exposure to light its conductance is nearly proportional to the intensity of the light

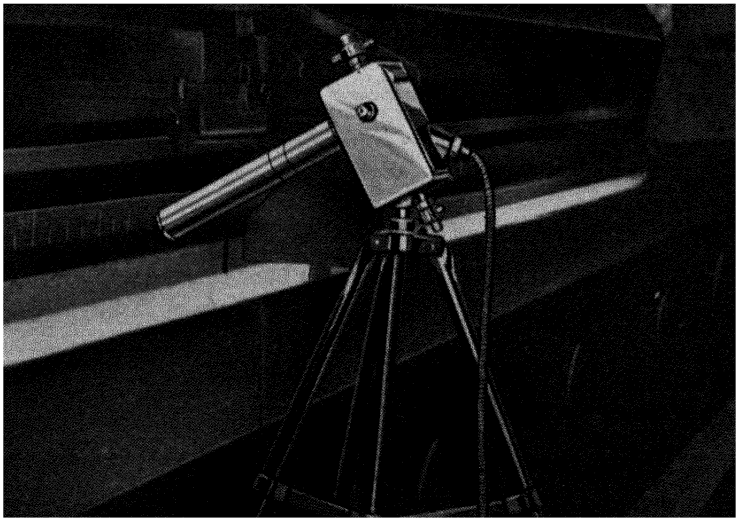


FIG 51 —Foster photo-electric pyrometer

falling on it. In the construction of the selenium cell or bridge the basic principle is the coating of copper, brass or silver, etc., plates with a thin film of metallic selenium. One application of the selenium cell is described and illustrated on p. 155 in relation to relay operation for recorders or controllers of temperature. Some of the particular properties of the lead sulphide cell are mentioned on p. 231 in relation to the estimation of the momentary high temperatures produced on metal tyres by heavy braking at high speeds.

The photo-electric cell is capable of responding to the varying temperatures of moving hot bodies where it may be important that the response should be practically instantaneous. By

making a suitable selection of the photo-electric cell, having due regard to the varying response of the cell to different wavelengths, the photo-electric current may change over a selected range much more rapidly with change of temperature than the Stefan-Boltzman fourth power law would suggest. This type of pyrometer is thus capable of indicating or recording the process of metal rolling and similar processes, and may provide additional means of controlling the quality and quantity of the products.

The Foster photo-electric pyrometer has been developed for such purposes. The photo-electric cell or receiver is suitably fixed inside the mounted case shown in Fig. 51 provided with hose connections for water cooling. For mounting it in a permanent position trunnion studs and nuts are provided. This receiver is of the fixed focus type with a definite cone of vision, and the measurement is independent of the working distance provided the cone is filled by the radiation from the hot body. These radiations within the cone fall directly on the photo-emission cell, there being no lens, mirrors, filters, condensers or adjustable diaphragms. The amplifier unit has one thermionic amplifying valve with the associated circuits accommodated on a spring-loaded sub-frame in a dust-tight case. While the amplifier unit should be placed as near to the receiver unit as is practicable to keep down the capacitance of the armoured cable, these units may be placed up to 200 ft. apart without causing erratic action or an excessive time lag and reduction of sensitivity between the receiver and the amplifier. The indicator or recorder or signal lights can be mounted at any reasonable distance from the amplifier. The recorder has a two-speed electric drive; and the continuous records on the chart on a time base occur with less than half a second of time lag, showing not only the temperatures of the separate billets, but, in addition, the lengths of the billets, the rate of production, and the duration of hold-ups. Two standard ranges are available, viz.: 800–1250° C. (1472–2282° F.) and 900–1300° C. (1652–2372° F.). With temperatures below 800° C. the photo-electric current may be too feeble to give accurate readings at the amplifier, especially when the amplifier is mains operated, because mains-borne disturbances cannot be easily excluded from the circuits.

CHAPTER V

GALVANOMETERS. INDICATORS, RECORDERS AND CONTROLLERS OF TEMPERATURE

Moving Coil Galvanometers.—Most electrical methods of indicating temperatures make use of a sensitive galvanometer of the moving coil type. In industrial installations the scale of the galvanometer may be divided into degrees of temperature and the instrument is then usually referred to as a temperature indicator. When the potentiometer method is used the galvanometer indicates by its null reading when two points in the electrical circuits are at the same potential.

The D'Arsonval moving coil type of galvanometer is represented in Fig. 52. The coil C of fine insulated wire is usually wound on a copper or aluminium former and is suspended or supported vertically between the poles of a permanent magnet M by metallic torsion wires or strips which also usually serve to conduct the small currents. A soft iron core I fixed between the poles of the magnet intensifies the magnetic field. When a current passes through the coil a mechanical torque or moment acts on the coil due to the interaction between the induced magnetic field and the magnetic field of the permanent magnet M. If the current is steady the coil is deflected by this torque against the controlling torque in the suspension wire until a balance is obtained. The faces of the magnet poles are usually made concentric with the coil and the deflection is then proportional to the current. In the arrangement shown a mirror L is fixed to the upper suspension wire and reflects a beam of light from a suitable lamp on to a semi-transparent scale. Well-designed galvanometers of this type are fairly "dead beat," that is, torsional oscillations are damped out rapidly by the effect of induced currents and the resistance of the air acting on the moving coil, or, in some cases, a suitable shunt resistance connected across the galvanometer coil may be used to give a dead beat effect for rapid readings. The angular movement of the coil may be shown by means of a pointer

moving over a scale instead of using a mirror but is not usually as sensitive in its indications. Levelling screws are usually provided on the base of the instrument to set the coil and suspension vertical. If a mirror galvanometer or indicator is used as a millivoltmeter to measure temperatures the readings should be practically independent of variations in the resistance of the leads whether due to changes of length or of temperature.

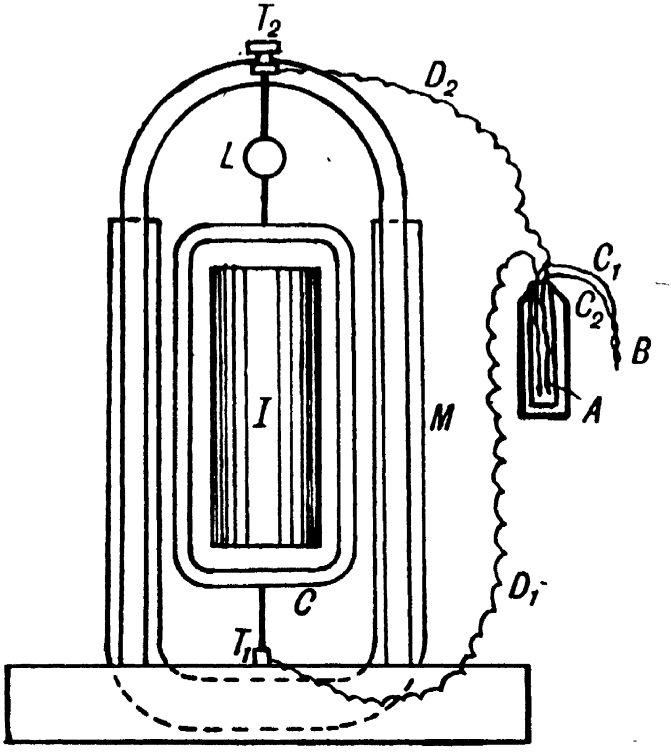


FIG. 52.—Moving coil galvanometer.

For this purpose the coil of a mirror galvanometer, or some portion of the circuit, should have a high resistance, and the coil may therefore be constructed to have a resistance of perhaps 800 to 1000 ohms. The suspension wire is necessarily of delicate construction and may be a flat strip or ribbon of phosphor-bronze having a fairly high elastic limit and little permanent change of elasticity. An adjusting screw is usually provided at the point of suspension so that the coil may be adjusted to the zero position.

The Campbell standard type of galvanometer is shown in

Fig. 53, with the cover removed. The controlling force on the coil is obtained by using bifilar suspension which thus avoids errors due to changes in elasticity and to the possible creeping of the reading after continuous deflection over a lengthy period of time. The horse-shoe magnet is laminated and levelling

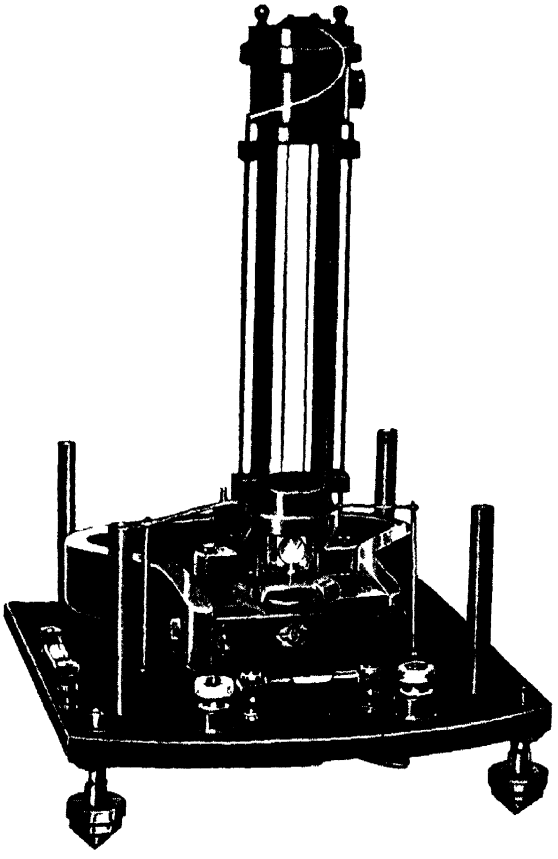


FIG 53.—Campbell galvanometer with bifilar suspension

screws enable the coil and suspending wires to be placed truly vertical.

The mirror galvanometer is essentially a laboratory type of instrument as the suspension system is too delicate for general use in industry, especially for a portable instrument. For ordinary working conditions makers build pivoted indicators in which the moving coil and pointer are supported in jewel bearings, and the controlling force on the coil is usually provided by a hair-spring of phosphor-bronze. Usually the coil

is supported on two pivots in jewel cups, one above and one below the coil. If the indicator has to be portable, or otherwise is liable to shock, or has to operate in conjunction with a "depressor" or "chopper" type of recorder, the jewel cups may be spring-mounted to relieve the effect of shock. For instance, the Foster Instrument Co. Ltd. have the two cups mounted on a central spring-supported pillar with the lower cup pointing downwards. Thus, under conditions of shock, the

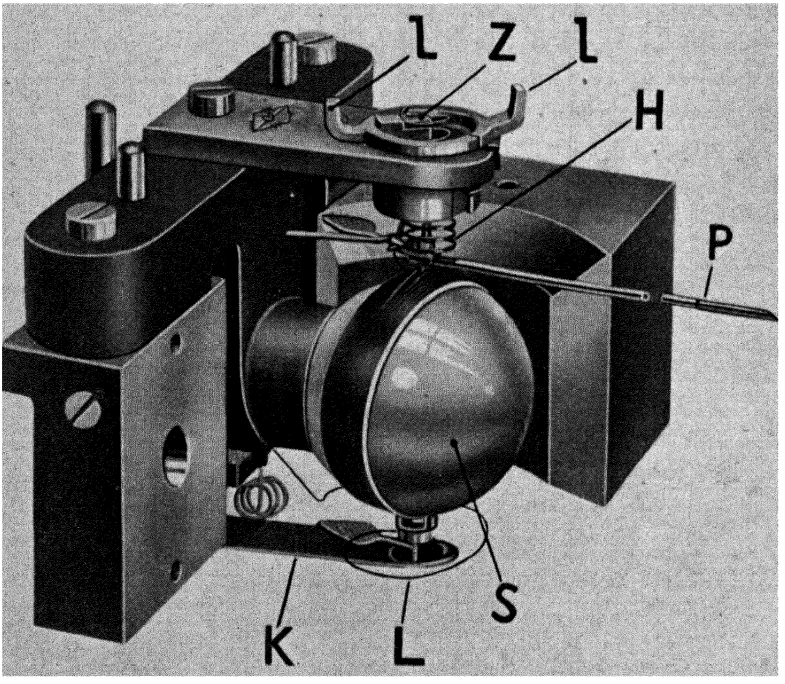


FIG. 54.—Single-pivoted type of galvanometer with pointer. (Cambridge Instrument Co Ltd).

bearings and the coil may move together without the pivots leaving the bearings. In the pivoted instruments made by the Cambridge Instrument Co., Ltd. the coil is supported magnetically in the magnetic field, thereby reducing the possibility of damage to the two pivots by shock and also reducing the frictional resistance at the pivots. The Bowen Instrument Co., Ltd. prefer to support the coil by means of a suspension ribbon, but in addition the coil is provided with a pair of pivots resting in jewel cups both pointing downwards so that the pivots do

not bear the weight of the coil and pointer, their sole purpose being to support the coil in a concentric position while allowing the pivots to " ride " in the bearings. The sensitivity of this indicator is at least equal to 10 ohms resistance of the coil per millivolt at full-scale deflection with the resistance of the coil 40–50 ohms. Thus as a millivoltmeter it may have a minimum range of 0–4 millivolts, but preferably it is perhaps better to select a minimum range of 0–10 millivolts to avoid errors because of possible variations in the resistance of the coil due to changes of temperature. Used as a microammeter a current of 100 microamperes through the coil will deflect the pointer across the scale. As a thermocouple indicator a range of temperature 0–200° C. across the scale can be provided with reasonable accuracy. At slight extra cost the same models may be modified to give a sensitivity of 40 ohms per millivolt if required. In the pivoted instruments levelling screws are not usually necessary. One arrangement of the moving parts and the fixed soft iron core of a single-pivoted galvanometer or indicator is shown in Fig. 54. The pivot is supported at the centre of the spherical core of soft iron in a jewel cup mounted on a light spring. The centre of gravity of the moving system is arranged to coincide with the central pivot and levelling screws are not necessary. A cylindrical spiral spring attached to the coil spindle provides the controlling force and also carries the current, while a flexible ligament connected to the lower end completes the circuit. The moving parts are shown separately in Fig. 55. When in transit or out of use a clamping arrangement raises the coil from the jewel bearing.

Reference was made on pp. 48 and 51 to the cross-coil type of indicator where the cross or control coil K of Fig. 20, p. 48, takes the place of a control spring. When the indicator is used as represented in Figs. 20 or 21 the reading obtained would be independent of moderate variations in the supply voltage.

A wall pattern single-point indicator is shown in Fig. 56 mounted on a swivelling bracket, as made by the Cambridge Instrument Co., Ltd. The numbers are boldly marked to show hundreds of degrees Centigrade for reading at a reasonable distance, and an anti-parallax mirror is fitted under the scale

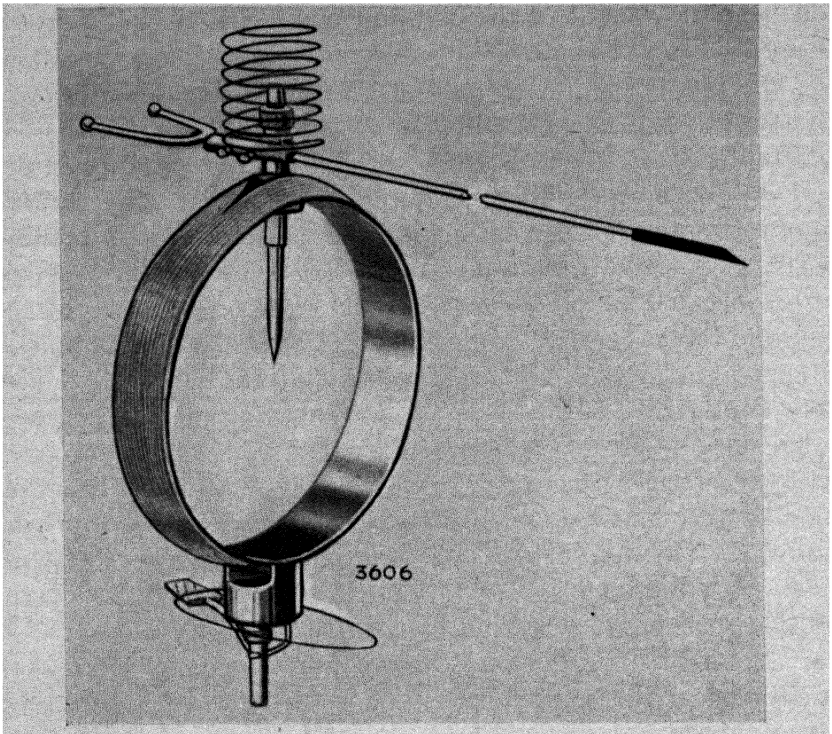


FIG. 55.—Moving parts of single-pivoted galvanometer.

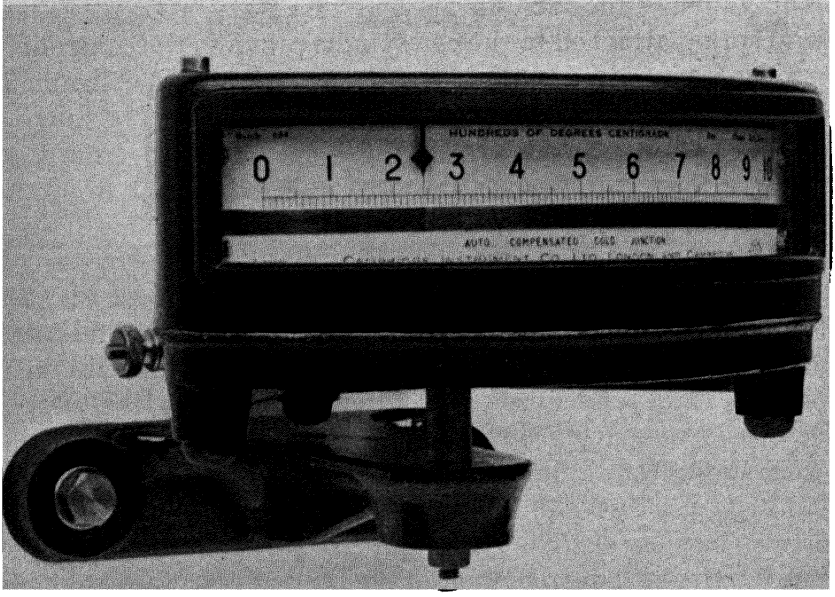


FIG. 56.—Cambridge wall pattern indicator.

to facilitate accurate reading. This instrument is fitted with an automatic cold junction compensator when installed with thermojunctions. In this illustration the reading on the scale starts at zero. Many industrial operations are carried out between certain narrow limits of temperature dependent on circumstances, and then it may be desirable to utilise the whole of the indicator scale for this limited range so as to obtain greater accuracy of reading. Electrical connections for this

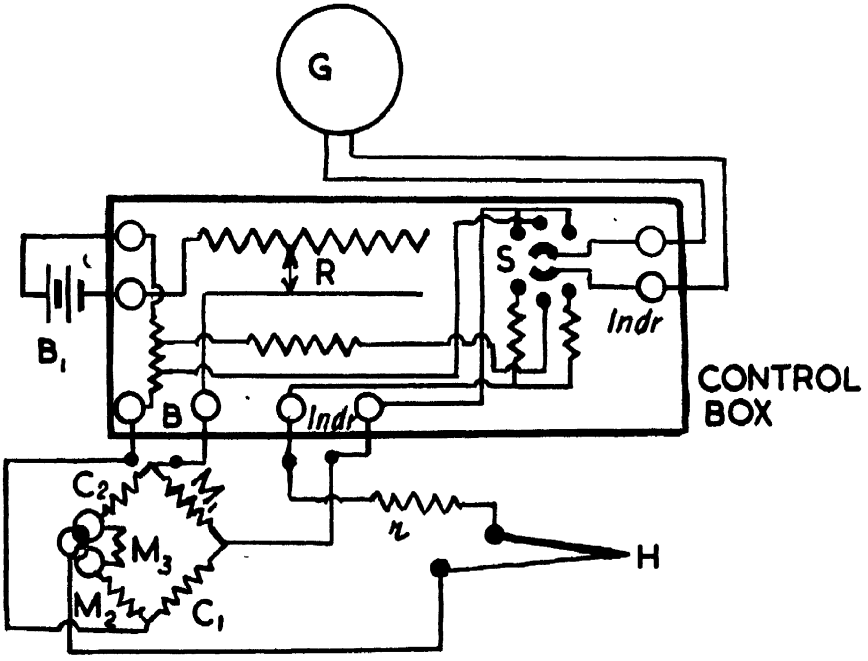


FIG. 57 —Arrangement to alter range of indicator, with cold junction compensator

purpose are shown in Fig. 57 in conjunction with an electrical cold junction compensator for use with thermojunctions. The compensator has the resistances C_1 and C_2 of copper in the two opposite arms of a Wheatstone bridge and the resistances M_1 and M_2 of manganin in the other two arms. The battery B_1 is connected across two opposite corners of the bridge through an adjustable resistance R while the thermojunction H and the indicator G are connected in series across the other opposite corners. When the temperature of the junction H and all connections are at a standard temperature, say 20° C. (68° F.),

the bridge is arranged to be in balance and no current flows through the indicator G with the pointer set at 20° C. If the cold junction temperature varies from the standard the bridge is thrown out of balance due to the difference between the temperature coefficients of the resistances of C_1C_2 and M_1M_2, and consequently a small out-of-balance current passes through the indicator G. The resistances are so proportioned that this current alters the reading of G by the amount of the change in the cold junction error. The cold junction compensator connections may be placed either at the head of the pyrometer or incorporated with the indicator some distance away. In the latter case the leads from the thermometer to the indicator should preferably be of the compensating type so that the cold junction is then situated at the indicator terminals. The compensator resistances may be adjusted to allow also for variations in the indicator reading due to changes in the temperature of the indicator coil and the control spring.

The rheostat R is adjusted to give a battery current of 0·1 amp., say, with the range setter switch S in the central position, and when the indicator G deflects to a red mark on the scale the rheostat R is in correct adjustment. If the indicator has two temperature scales, one of which may correspond to the full range of temperature and the other to an expanded range, or, alternatively, two expanded scales may be provided, either of the two scales may be brought into use by setting the switch S to the corresponding mark, which simply alters the resistances in circuit with the thermojunction H. At the same time the connections for the cold junction compensator resistance M_3 are altered by inserting a screw or plug into one or other of two positions which throws M_3 into one or other arm of the Wheatstone bridge arrangement, and in effect introduces some e.m.f. from the battery into the thermocouple circuit. For instance, an indicator may have the scale 0–600° C. for one purpose and a more extended scale, say 300–600° C. for greater accuracy of reading between these temperatures. A reference to the table on p. 61 in respect to the iron-constantan couple shows that in this case the battery would need to provide nearly 16·9 millivolts in opposition to the thermojunction at 300° C. after allowing for the cold junction compensation. If the indicator range 300–600° C. only were required the connections

for the switch S and the coil M_3 in Fig. 57 could be simplified to that extent. In this case, however, an alternative method could be adopted whereby the indicator control spring was designed for such a range by providing a reverse torque on the spring control to suit the initial reading required. In some indicators the cold junction compensation is obtained by means of a bimetallic strip attached to the control spring so that the indicator reading on open circuit is the temperature of the surroundings. In the potentiometer system the cold junction compensation is commonly provided by a suitable copper resistance in the circuit, such as is represented by CJC in Fig. 32, p. 73.

The moving coil of the galvanometer or indicator should be effectively insulated and have free movement. Direct contact of the coil with the stationary parts is easily prevented, but the rubbing of filaments from the insulation or of accumulations of particles of iron dust on the magnet poles should be guarded against. The readings should not be influenced by stray currents or by the magnetic effect of lighting or power circuits, or by large masses of iron or steel in the neighbourhood. The moving coil instruments are not usually very sensitive to magnetic disturbances of this character, especially if the casing is made of iron or steel, but they should be calibrated with the casing in place and earthed if necessary. Thermo-electric effects due to differences of temperature at lead connections, and electrolytic currents and bad contacts in damp situations, should be avoided.

Deflection instruments for the laboratory may be designed and calibrated to read in millivolts, and temperatures of thermo-junctions would be deduced from the millivolt readings. While this method may be used occasionally in industrial operations, in general it may not be convenient when compared with deflection instruments designed to read temperatures directly with the particular thermocouples for which they were calibrated. A thorough calibration should cover a reasonable range of the ambient temperature conditions. The British Standard Code 1041:1943 on "Temperature Measurements" suggests that for temperature indications corresponding to a range 0–20 millivolts the limit of variation allowed due to a change of $\pm 1^\circ$ C. in the ambient temperature should not

exceed 0·25%, and for a range 20–50 millivolts should not exceed 0·2%.

When a deflection instrument is used with an electrical resistance thermometer, as represented in Fig. 21, p. 51, the temperature coefficient of the instrument is not likely to cause serious errors in the measurement of temperature because a "test" adjustment reading is, or should be, applied before the thermometer readings are taken.

When a sensitive galvanometer is used to indicate a balance of potential by the null method, as in Figs. 13 and 30 on pp. 41 and 70 respectively, the ambient temperature can have no appreciable effect on the accuracy of the reading, apart from the cold junction compensation in thermocouple arrangements where the cold junction is at the galvanometer or has the same temperature.

If a sensitive galvanometer is used the null method is likely to give a more accurate reading of a steady temperature than the deflection method, more especially if the deflection instrument were not well calibrated for the conditions of operation, or if the calibration were not allowed for in practice. The null method, however, requires some manipulation to obtain a reading, either by hand in simple arrangements or automatically in more complicated installations. If the adjustment were to be made by hand, as in Fig. 30, p. 70, usually the adjustment is made first to one side of the null position and then to the other side, and in this way edging the adjustment on to the null position. This action may thus take a little time to complete, even with a steady temperature, and renders it difficult to follow changing temperatures accurately.

A "ballistic" galvanometer may be used to measure a quantity of electricity on discharging the electricity through the moving coil. The moving parts are designed to have a comparatively large moment of inertia in order that the whole of the discharge shall pass through the galvanometer before the system can move appreciably from the zero position. The air resistance should be as small as possible. Under these conditions the impulse given to the coil causes it to deflect, and it can be shown that the maximum throw obtained is proportional to the quantity of electricity causing the impulse. Owing to the large moment of inertia the period of oscillation

may be a long one, say 10 or 15 seconds, and to save time in bringing the galvanometer to rest at zero, provision is usually made for short-circuiting the coil temporarily. The ballistic type of galvanometer has been used * to determine the fluctuating temperatures in the cylinder wall of a steam engine. The instantaneous measurement of the e.m.f. was made by inserting the galvanometer into the thermocouple circuit for each measurement. This was done by means of a falling weight contact apparatus at equal intervals of 0·2 second. A short account was given in the lectures mentioned on p. 224.

At the other extreme is the " oscillograph " type of galvanometer which is required to follow the impressions of a rapidly fluctuating potential or current and the natural period of oscillation of the instrument should be much shorter than that of the fluctuations to be measured. If the natural period of oscillation were to coincide with the period to be measured, or with an important harmonic, the tendency would be for the instrument to acquire a state of impulsive oscillation, and the amplitude of the swing would not then have any necessary reference to the amplitude of the impulses. Such an instrument, then, should have a moving system with very small inertia, and the coil may be reduced to one turn or even one-half turn. One arrangement which has been used to measure the fluctuations of temperature in the cylinder walls and the working fluid in reciprocating engines is the Einthoven string or thread galvanometer. This galvanometer consists of a fine rare metal or metal-coated filament stretched with a suitable tension across a strong magnetic field. The filament carries the small current passing and the magnetic reaction causes a deflection of the filament across the magnetic field according to the value of the current and the tension in the filament. The scale of the deflection and the natural period of oscillation are adjustable by the means provided for altering the tension of the filament. This period of oscillation may be of the order of $\frac{1}{2000}$ second, and thus there is little danger of the impressed deflection of the filament at engine speeds being seriously disturbed by the natural oscillations of the filament itself. The movement of the central part of the filament may be observed

* " Les Phénomènes Thermiques dans les Machines à Vapeur," A. Duchesne, *Revue de Mécanique*, Vol. II, 1906.

either through a microscope or from an image projected on to a screen through a slit, or a record may be taken on a moving photographic plate or film. A further description of particular arrangements of the Einthoven galvanometer is given on pp. 226 and 228.

The adjustable contact maker and potentiometer method of measuring the indications of thermojunctions in following the fluctuations of the temperature of cylinder walls was used in the experiments described in the first few pages of Chapter VIII. This method has some disadvantages. In the first place a complete set of readings for one point takes some time and is the result of many cycles. If a number of points have to be dealt with in this manner it is almost impossible to secure complete steadiness in the operating conditions over the required period of time, and experimenters were thus compelled to arrange the thermojunctions to give the fluctuations of temperature above or below the mean temperature of the wall to obtain consistent results. There is also the possibility of erratic disturbances caused by the generation of static electricity due to rubbing friction at the contact maker. If it could be said that the above method had been superseded by the Einthoven thread galvanometer in the measurement of fluctuating temperatures, there is reason to expect that this galvanometer in turn is being displaced for this purpose by the cathode ray oscillograph or oscilloscope.

The Cathode Ray Tube.—In a simple form the cathode ray tube consists of an exhausted glass tube 18 to 26 in. in length and 6 to 14 in. in diameter at the large end. The inside of the large, nearly flat, end of the tube is coated with a fluorescent material such as calcium tungstate or zinc silicate. As illustrated in Fig. 58 the narrow end of the tube has the filament or cathode K which is heated by a current, either directly or indirectly. The heating effect causes an emission of electrons which tend to form as a cloud near the filament and to prevent this and to cause the ejected electrons to pass on with a high velocity the disc anode A_1, having a central hole, is fixed in position in front of the filament or cathode, being kept at a moderatively high potential relatively to the cathode. This causes the anode A_1 to attract the electrons and accelerate them towards itself, with the result that some electrons pass through the

central hole at a high velocity. The electrons leaving the filament cathode tend to repel one another and spread out because of the repulsion of similar charges, so that most of them would strike the anode A_1 were it not for the presence of the shield S placed round the filament. This shield is kept at a suitable negative potential and thus tends to repel and " focus " or concentrate the electrons towards the central hole in the anode A_1. The stream of electrons still tend to repel each other after passing through the central hole in A_1, and to control this action and to concentrate or " focus " the stream on to the fluorescent screen the cylindrical anode A_2 is kept at a suitable voltage higher than that of A_1, while the accelerating

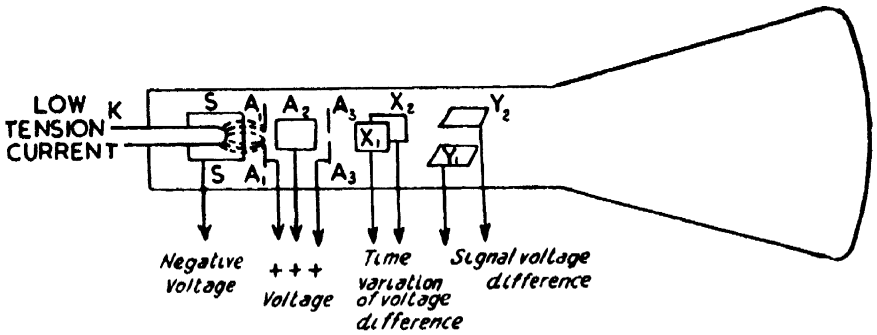


FIG. 58 —Cathode ray tube.

anode A_3 is maintained at a still higher voltage. The point on the fluorescent screen on which the electrons strike shows up as a spot of light.

The purpose of the two sets of plates X_1X_2 and Y_1Y_2 at right angles to each other is to induce the spot of light to move over the screen. When the plates X_1X_2 are subject to a difference of potential this causes the deflection of the stream of electrons in the horizontal plane depending on the potential difference, which is usually altered on a time base. In a similar manner the potential difference between the plates Y_1 and Y_2 causes the stream to be deflected in a vertical plane dependent on the signals of potential received. These actions usually take place at high speeds with the result that the spot of light moving over the screen gives the impression of a continuous line of light which may be recorded by photography. It is usual to synchronise the time base on X_1X_2 into unison with

the signals or impulses on Y_1Y_2 so that the path of the point of light on the fluorescent screen is reproduced continuously and successively. The electrical impulses may have to be modified or magnified before reaching the X_1X_2 or the Y_1Y_2 plates so as to produce a very rapid "flash back" to the beginning of the X_1X_2 base line, and a reasonable scale of reading or recording on the Y_1Y_2 axis. Thermionic valves or tubes may be used for these purposes. For more detailed information reference should be made to special work on the subject.*

In some special arrangements varying magnetic fields are used instead of potential differences. The stream of electrons is then deflected at right angles to the magnetic fields.

Temperature Recorders.—In modern industry the recording of temperatures on a timed chart is often required to obtain a check or record of the controlling conditions. The recorder may be placed near to the site of the operating plant or may be installed in a central office at a distance from the thermometers or pyrometers. In the latter case an indicator also may have to be installed for the guidance of the operator. The recorder may be of the circular or dial type where the chart is usually changed daily, or of the drum or continuous strip type where the chart may be arranged to run for periods up to a month. The use of the dial chart with mercury-in-steel thermometers was mentioned on p. 32. It is also frequently used with electrical thermometers, and one arrangement is represented in Fig. 82, p. 171, where the pen marks the chart directly. In the form built by the Foster Instrument Co., Ltd. the chart is translucent and lasts for 24 hours. The stylus of the deflection pointer is pressed periodically by mechanical means on a sheet of carbon behind the chart and this gives a series of dots on the chart, thereby leaving the pointer free to take up its position without interference between the markings. The mechanism is driven by a synchronous electric motor. Where d.c. only is available a d.c. to a.c. rotary converter can be supplied. The strip type of recorder is commonly adopted in important plant using electrical thermometers, either as a thread recorder in deflection instruments, or having a travers-

* *The Oscilloscope. Design and Construction*, by J. A. Hopkins (Bernard (Publishers) Ltd.), London.

ing ink pen in potentiometer instruments. A thread recorder is illustrated in Fig. 59 made by the Cambridge Instrument Co., Ltd., and most British makers build similar models operating on the same principles. In this thread recorder the indicator pointer moves freely over the temperature scale with the underside blunt knife edge nearly in contact with a coloured ink thread stretched across the top of the chart. Every 20 to 30 seconds a "chopper" bar or "depressor" operated by a suitable cam is lowered and presses the pointer and the inked thread on to the chart, thus leaving a dot or mark on the chart as the bar is raised out of contact, and the sequence of marks gives the record. This arrangement leaves the galvanometer needle free to take up its true position without excessive friction. Up to six points may be recorded automatically on one chart, using one galvanometer, by having up to six different coloured ink threads mounted on bobbins on an automatically movable frame. The bobbins are rotated periodically to bring fresh parts of the threads into operation. Each thread is brought in turn underneath the pointer in unison with the corresponding thermometer or pyrometer brought into the galvanometer circuit by an automatically operated switch. The galvanometer pivots or suspension has to be made robust enough to stand up to the frequent depression of the needle. Four such records are shown on the chart in Fig. 59 and the number of the thermometer in the circuit is shown (4 in this case). In this recorder the chart is 127 mm. (5 in.) wide and lasts one month at a speed of $\frac{1}{2}$ in. per hour, showing in view the record of the last 18 hours. The chart is readily changed on opening the dust-proof door. In this model the mechanism is driven electrically from the mains supply but similar models are usually available driven by a clockwork mechanism. If the recorder is used with thermocouples an automatic cold junction compensator may be incorporated, or, if used with the distance thermometer,

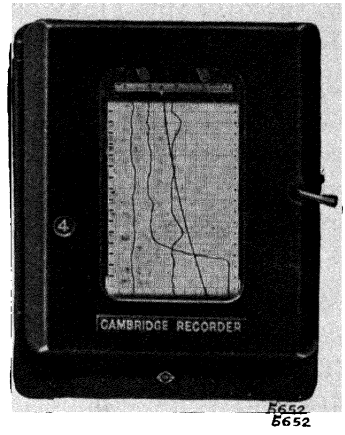


FIG 59.—Thread recorder.

represented in Fig. 21, p. 51, a test switch and bridge arrangement would be introduced.

The ink pen type of recorder has the position of the pen on the chart determined through some form of mechanical or electrical amplifier having sufficient power to overcome any frictional resistance of the pen mechanism. Several of these operating features are described later in relation to systems of temperature control.

Temperature Regulators or Controllers.—The automatic control of the temperatures of furnaces, ovens, hardening baths, lead baths, moulding presses, heated rolls, buildings and the like is of increasing importance in modern industry. The methods adopted may depend on the importance of the process and on the size of the plant undergoing control, as well as on the temperature to be controlled, on the relative cost of the controlling instruments, and on the possible or probable savings which may be effected, including the factors of improved quality of the product with reduced wastage, and the increased output of the plant under control.

The various arrangements for the control of temperatures may generally be included in one or other of the following systems.

1. Pressure or expansion elements sensitive to changes of temperature operating the control on the heating system electrically, or operating control valves mechanically or electrically, or a combination of these methods.

2. Pressure or expansion elements sensitive to changes of temperature operating control valves either pneumatically or hydrostatically.

3. Electrically sensitive temperature elements operating the control on the heating electrically, or operating control valves electrically.

4. Electrically sensitive temperature elements operating control valves either pneumatically or hydrostatically.

Every heating process has a definite rate at which the temperature comes to equilibrium after a change in the conditions dependent on the heat storing capacity of the plant and on the rate of heat supply, as well as on the rate of loss of heat. The controller should permit of easy adjustment of stability and synchronisation with this equilibrium rate without serious "over-shooting," "hunting" or "drifting."

The " two-position " or " two-step " or " on-off " control is suitable in many cases where the heating process is continuous. In the " on-off " system all, or nearly all, the supply of heat is turned on when the temperature falls below the selected value by a given amount, and is nearly all turned off when the temperature rises above this selected value by a similar amount. The change of temperature between these two points is often referred to as the controller " differential." In the " high-low " system of control the supply of heat fluctuates between upper and lower limits. For example, in a gas-fired furnace having " high-low " control, the controlled gas valve may be fitted in a by-pass arrangement with the other direct supply valve pre-set to give nearly the required supply of gas. When the temperature falls below the selected value by a given amount the controlled valve is opened to augment the gas supply and thus causes a rise of temperature. When the temperature rises above the selected value by a similar amount the controlled valve is again closed and the temperature falls, and so on alternately. In this case the timing periods may be much longer than in the " on-off " type of control.

The simplest form of " two-step " electrical controller has a single-pole single-throw mercury switch or contacts controlling, say, a spring-loaded solenoid valve. In the " two-step " three-wire system commonly adopted for the control of a motor or motorised valve one position of the switch energises one pair of the three wires, and in the other position another pair of the three wires is energised. The motor usually contains a maintaining switch to relieve the controller switch of the strain of breaking the operating current or to ensure complete action on a momentary contact by the instrument.

A modification of this system sometimes adopted is the three-position or " three-step " control having a medium position switch. The medium selective position may be of the order of 2% of the scale range below the high position. The amount of energy cut out between the high and medium switch position is less than with two-step control, and the variation of fuel intensity is less.

In " floating " electrical control a single-pole double-throw switch is used having a " dead " neutral position where no contact is made between the limits of the controller differential.

The controlled substance or condition, say a reversing motor, runs in either direction under the command of the controller, but does not move when the controlling medium or physical quantity (temperature in this case) is between the limits of the differential.

In the " proportional " or " modulating " system of control the variations in the rate of heat supply are more gradual than in the " two-step " system, and the term " proportional " is used because the change in the rate of fuel supply is proportional to the deviation from the desired value when a variation of temperature occurs from the selected point or " desired value." When any unbalance occurs due to changes in the detecting element the controlled condition, say a motor, moves to restore the balance. Hence a definite motor position is obtained for every position of the controlling unit. The difference of temperature which causes the flow of heat to change from the maximum to the minimum values is termed the " proportional band " or " throttling range." A plant operating at high temperatures usually has a large storage of heat and it may be possible to set the proportional band at a small value without causing " hunting " of the conditions. If this band were made too large drifting from the control point or desired value may occur. When a change has taken place in the detecting element (temperature) from the set point or desired value and a new position of balance has been obtained, the new balancing temperature may not be quite the same as the desired value. In important installations the controller may be made to " re-set " the temperature at the desired value, which may be done by hand in some cases, and in other cases done automatically. Combinations of proportional and floating control, with or without re-set control, are sometimes adopted.

The term " controller differential " usually refers to the changes in the detecting element required for the control and not to the corresponding changes in the controlled medium, substance or condition, which may not be the same. It is of some importance to place the detecting element in a position where its range is as nearly as possible the same as that of the controlled condition. In the best arrangements the rate of change in the conditions is usually slow and is fairly even

throughout the heated substance or condition. Where control is obtained through a thermostat immersed in the controlled medium it is evident that the thermostat will usually lag behind the change of temperature of the medium. Therefore the " differential " of the thermostat is likely to be less than that of the controlled medium (usually air or water) dependent on the intimacy of the contact, that is, the fluid surrounding the thermostat should not be stagnant. In some processes the temperature may be required to follow a controlled programme for heating in batches, such as a rising temperature at a definite rate or rates with a period of constant or " soaking " temperature, followed by a falling temperature at rates suitable for the process. The desired temperature has to be varied accordingly and is usually obtained by the action of a cam cut to a suitable form operating on the setting mechanism.

The pressure elements sensitive to changes of temperature most commonly used are the liquid or mercury-in-steel, the vapour pressure, and the gas pressure types of bulbs described on pp. 27–32. Although these pressure thermometers may not be as accurate as electrical thermometers or pyrometers used in conjunction with the potentiometer or Wheatstone bridge types of controllers, and may be suitable only for temperatures lying between, say, −40° C. (−40° F.) and 600° C. (1112° F.), they usually possess the important feature of robust construction and simplicity of action, together with moderate costs of installation and maintenance.

The element is usually required to operate an indicator or recorder as well as to function as the actuating element in the controller. The elastic tube or bellows or similar expansion device is used in some designs to make electrical contacts when the pointer or pen reaches the predetermined position of the control temperature. The making or breaking of these contacts is arranged to operate an electrical relay or contactor or a mercury-in-glass switch, which in turn closes or opens electrical heating circuits, or operates the valve controlling the supply of heating fuel or of steam. These contactors or relay switches may carry up to about 30 amps. at line voltages with a non-inductive load.

The arrangement of a thermograph or record chart regulator and contactor due to the Cambridge Instrument Co., Ltd. is

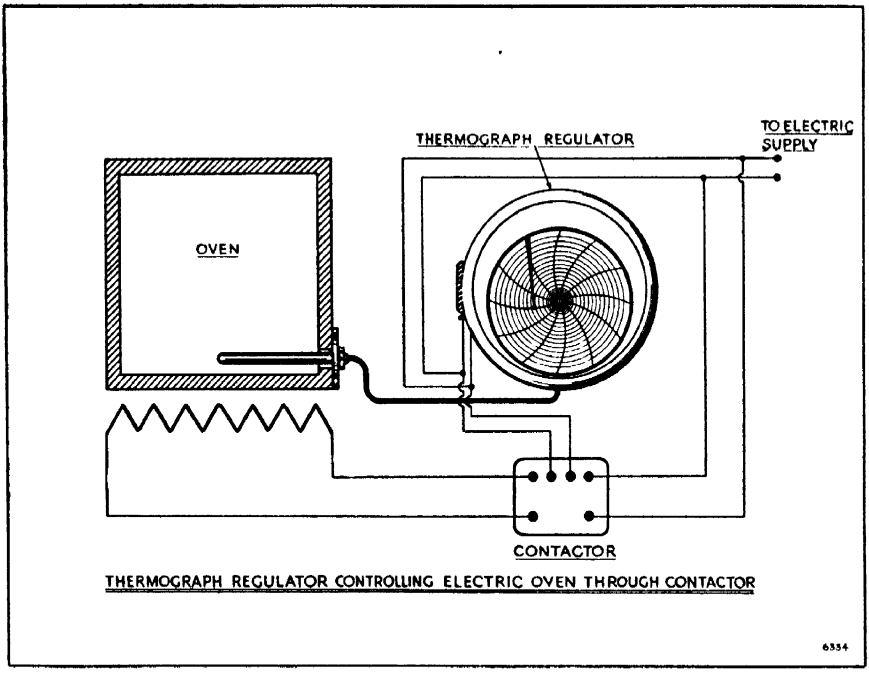

THERMOGRAPH REGULATOR
TO ELECTRIC SUPPLY
OVEN
CONTACTOR
THERMOGRAPH REGULATOR CONTROLLING ELECTRIC OVEN THROUGH CONTACTOR
6354

FIG. 60.

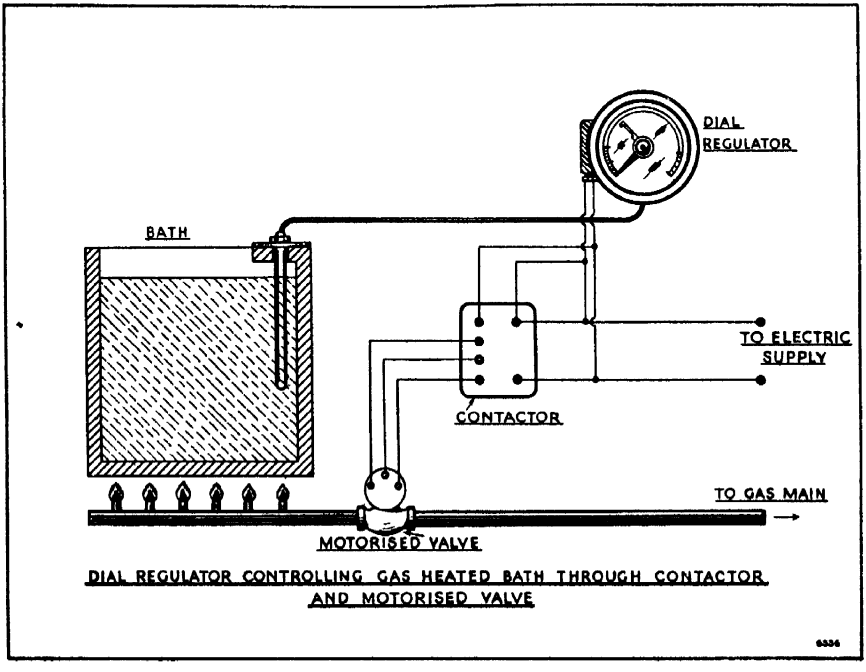

DIAL REGULATOR
BATH
TO ELECTRIC SUPPLY
CONTACTOR
TO GAS MAIN
MOTORISED VALVE
DIAL REGULATOR CONTROLLING GAS HEATED BATH THROUGH CONTACTOR AND MOTORISED VALVE
6336

FIG. 61.

represented in Fig. 60 with an electrically heated oven. The temperature sensitive pressure bulb actuates the recorder pen and is arranged to close spring-loaded electrical contacts when the pen reaches the pre-set control temperature, and this in turn causes the contactor or relay to open the heating circuit, thus operating on the "on-off" system. This regulator or controller can be arranged to vary the controlled temperature according to a programme by introducing a cam cut to suitable shape which is rotated at the chart speed. The instrument can be used as an ordinary regulator by removing the cam and setting the control temperature to the required value.

The similar arrangement of a temperature sensitive pressure bulb and dial regulator is shown in Fig. 61 operating a contactor and motorised gas valve controlling the gas supply to a heated bath. In the closed position an internal by-pass provides a pilot light with gas to relight the main burner.

Fig. 62 shows the arrangement of a Cambridge Instrument Co. gas regulator controlling the temperature of a lead pot through a low pressure relay valve where the gas pressure does not exceed 10 in. of water gauge. For higher gas pressures a high pressure relay valve is used. The temperature sensitive pressure element immersed in the molten lead operates a standard 4-in. dial thermometer fitted with adjustable spring-loaded contacts controlling a small solenoid gas valve operated from the electric mains supply. This valve is accommodated with the dial mechanism in a rectangular case and supplies the gas pressure to the diaphragm of the gas relay valve in the main gas supply line. Nine standard sizes of these gas valves are available suitable for pipes from $\frac{1}{2}$ in. to 3 in. bore, and may be used for gas pressures of a few inches of water gauge up to 4 lb. per sq. in. An internal by-pass is provided in the gas valve which prevents the burner from being extinguished when the control operates to close the valve. The flexible tubing connecting the sensitive bulb and the dial is usually 6 ft. long, but may be made of much greater length if it is desirable to place the dial well away from fumes or heat. Several standard ranges of temperature are available up to a range of 100–600° C.

The dial thermometer can be arranged to operate alarm signals, such as Klaxon horns or coloured lights, when the

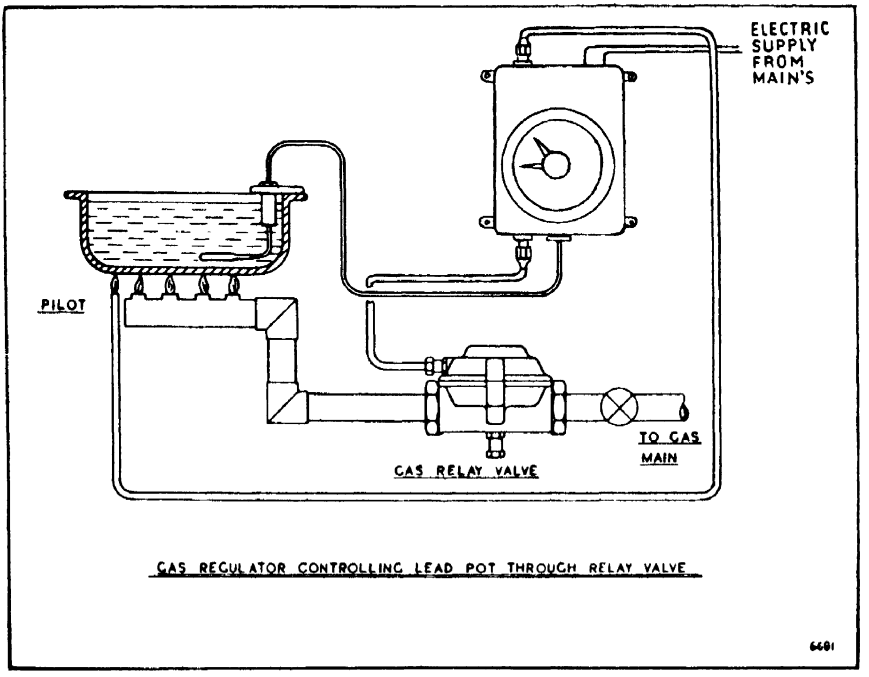


FIG. 62.

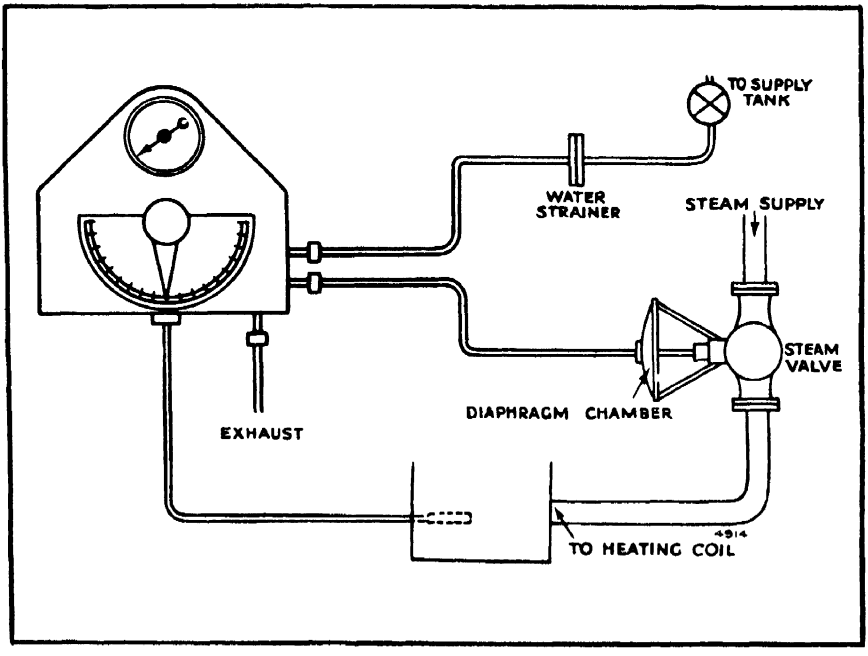


FIG 63.—Hydrostatically controlled steam valve.

temperature reaches a maximum value and/or when it falls to a minimum value.

Similar bulb thermometers are adapted to the control of the flow of steam, gas, oil, air, water, or other fluids, through pneumatic or hydrostatic operated valves. Such a regulator controlling the steam supply to a chamber or coil through a hydrostatically operated diaphragm valve is represented in Fig. 63. Below the indicator is the hand-operated pointer to set the temperature of control. The controlled valve in the steam supply pipe (or other means of heat supply) is fitted with a diaphragm chamber so that when a suitable air or water pressure is applied to the diaphragm the valve is closed, or, in the reverse arrangement, is opened against a spring load as may be the case. An advantage of the reverse arrangement is that a failure of the diaphragm pressure would cause the valve to close. The pressure operating the diaphragm valve should be steady for the best results. A reducing valve fitted to the main supply may be used to reduce the pressure to 8–15 lb. per sq. in. When water pressure is used a tank with a ball valve may be installed not less than 20 ft. above the control valve to give a steady pressure.

In the Cambridge Instrument Co. arrangement the water or air pressure is applied through the regulating device shown in Fig. 64. The thermometer bulb G exposed to the temperature to be controlled is connected by capillary tubing to the Bourdon tube in the dial or recorder and also to a second tube A. This tube A is connected by the link B to a lever C which is pivoted on the diaphragm D and projects inside the chamber E to control the position of the valve F. The water or air at pressure is supplied through the pipe H to a small orifice R leading to the pipe L which in turn is connected to the diaphragm of the control valve. The pressure in L depends on the opening of the orifice S under the control of the valve F. When the temperature is below the control value the pressure tube A takes up the position shown in the diagram with the valve F open. Since the area of the orifice S is much greater than that of the orifice R there is but little pressure in the pipe L and, in the direct action arrangement, the control valve will be open. As the temperature rises the increased bulb pressure opens out the tube A with the result that the lever C is tilted

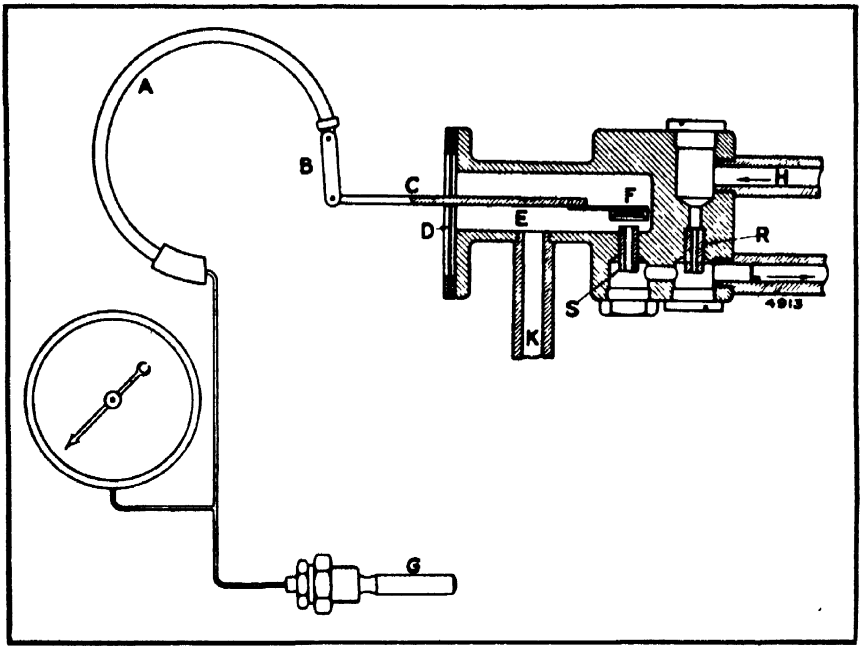


FIG. 64.—Pneumatic or hydrostatic control (Cambridge Instrument Co. Ltd.).

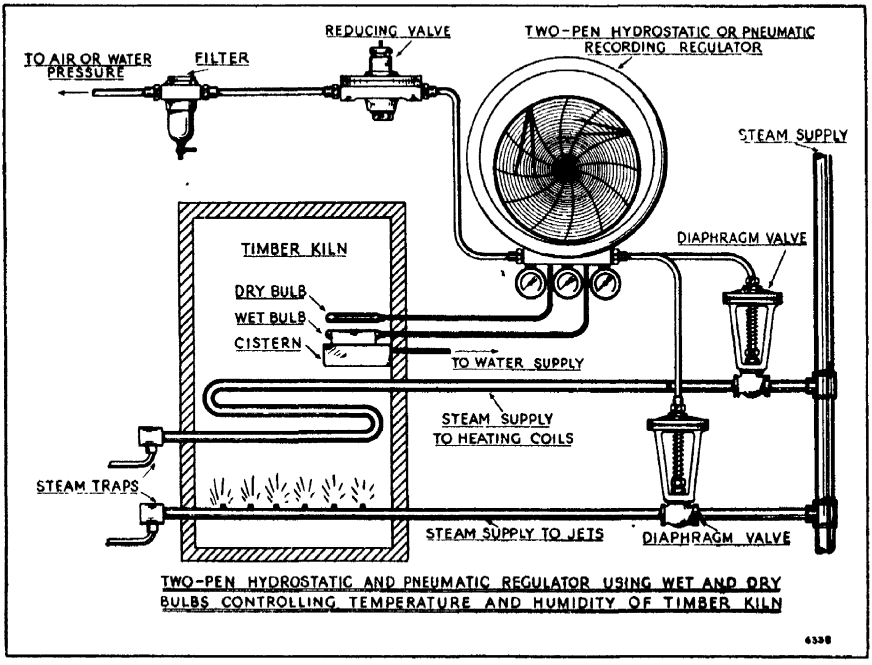


FIG. 65.

so as to close the valve F, which then causes the pressure in L and on the diaphragm of the control valve to rise and close this valve. In practice, when the control temperature is reached the lever C soon takes up a position such that the valve F partially closes the orifice S. By this means a more or less constant pressure acts on the diaphragm holding the valve in the required position according to the bulb temperature, and thus gives proportional or modulating control. Double regulators for the control of temperatures at two different points

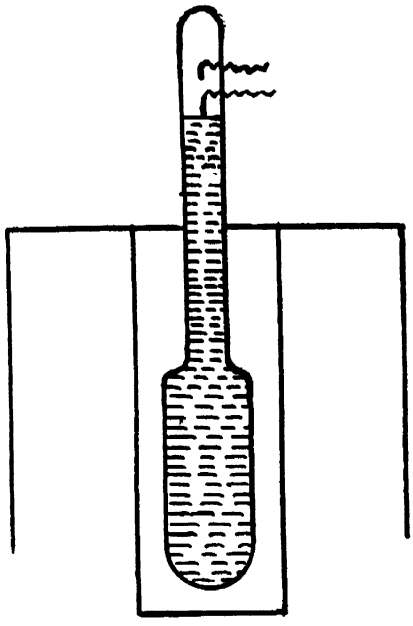


FIG 66.—Simple mercury contacts.

are available, and when fitted with wet and dry bulbs the instrument provides a means of controlling humidity. Such an arrangement for controlling the temperatures and the humidity inside a timber kiln is shown in Fig. 65 due to the Cambridge Instrument Co. Ltd. An arrangement of humidity control using resistance thermometers was described on p. 53.

A form of mercury electrical contact sometimes used in simple "on-off" temperature controllers for a fixed temperature is shown in Fig. 66. The mercury in the bulb expands or contracts with change of the temperature and makes or breaks the electrical contacts in the stem to operate a relay.

There is a considerable field of application for simple controllers up to temperatures of about 300° F. where the controller is not itself used to operate a temperature indicator or recorder. A thermostatic control system is represented in Fig. 67 and is built by Messrs. Sarco Thermostats Ltd., of Cheltenham, Glos. There are several different valve arrangements actuated on the same thermostatic principle. In Fig. 67 the thermostat 1 may be fixed to a suitable board for ambient air or gas temperature control, or immersed in a liquid whose temperature is under control. Inside the case or cover 1 is a spirally corrugated bellows tube 10 with a tight solid lower end or plug, and it is fixed tightly at the top end to a similar piece bored to take the freely sliding rod or plunger 8. This rod rests on the lower end of the spiral tube being pressed into contact by the spring 9 with a force adjustable by the regulating screw 7 according to the control temperature required. The space between the case 1 and the spiral tube 10 and the space in the capillary tube 2 right up to the similar space between the case 3 and the spiral corrugated tube 10 of the valve extension, is filled with an expansible mineral oil.

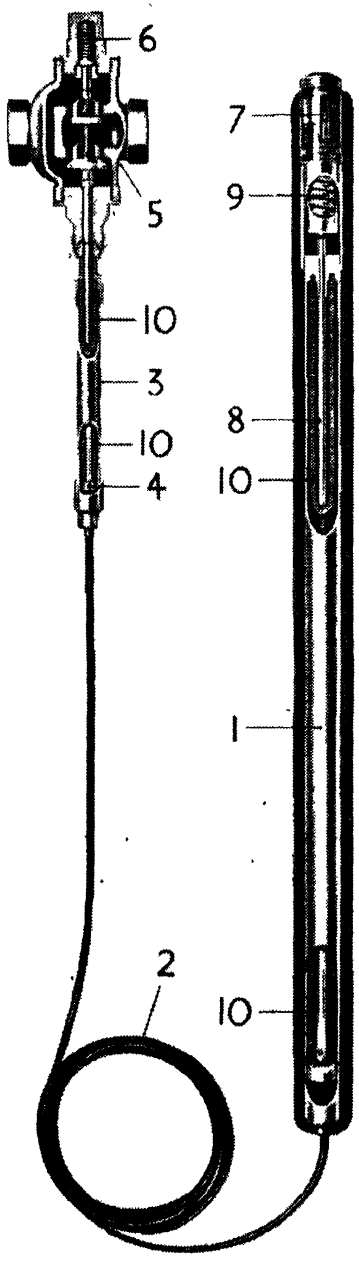


FIG 67.—Sarco thermostat pressure-operated controller.

When the temperature of the thermostat rises the pressure increases proportionally and the pressure, acting on the rod or plunger 4, moves the valve towards the closed position against the spring 6 when the valve 5 supplies the heating medium. If the purpose is to provide a cooling medium, as in the jacket cooling of internal combustion engines, or in the cold storage rooms of a refrigerating plant, the operation is arranged to increase the valve opening. The control of the temperature in this arrangement is on the " modulating " or " proportional " system.

For water heating systems the valve may be arranged to mix or blend the water from the hot-water supply at a predetermined temperature with some of the cooler return water, in the proportions required to give a flow of water to the heater system at such a temperature that the heat emitted balances the loss from the building at the required temperature of the building. The extent of heating surfaces in the form of radiators and pipes installed in a building is based on the maximum temperature required in the building when the outside temperature was at its lowest. With higher outside temperatures the heat supply required is less and the temperature of the water circulated round the system should be lowered. If the control on this temperature were solely dependent on the change of temperature in the building this latter temperature might be subject to undesirable fluctuations. On this system, however, the mixing or blending valve may be controlled by a thermostat exposed to the outside temperature, which thus anticipates the necessary position of the valve.

In the system adopted by The Rheostatic Co., Ltd., of Slough, Bucks., an outside or " Pilot " thermostat has some control on the temperature of the heating water given by the boiler or calorifier. Another thermostat controls the supply of heat to the boiler furnace. Further thermostatic control may be necessary where a building, or a part of the building, is subject to varying conditions, or which accommodates heating processes, or which has machinery where frictional energy is dissipated.

The mixing valve may be of the divided piston type with treble ports, and can be arranged to be operated directly by the thermostat where the plunger or central rod becomes an

extension of the valve spindle. In this form it is used for the mixing of hot and cold water, brine or other liquids, and delivering the mixture at any predetermined constant temperature up to 300° F. It has many applications, such, for instance, as wash water in the food and dairy industries, laundries, baths, etc. It is also used in regulating the jacket water temperatures of internal combustion engines, air and gas compressors, and the brine temperature in refrigerating plant.

The same firm supply a simple form of water heater working on the principle of the steam injector, for use in hot-water systems, including the heating and circulation in hot-water tanks and the like. The free end of the thermostat has a stainless steel ball facing the mouth of the steam nozzle and operates as a steam valve of variable opening according to the temperature of the water by the regulation of the axial position of the ball in relation to the nozzle.

The Rototherm thermometer, operated by a coiled bimetallic strip as described on p. 32, is also available for temperature control of the " two-step " or " on-off " type. When used as a controller the indicator is provided with a moulded ring of insulating material in which is mounted an adjustable pointer carrying a contact. The indicator pointer carries a similar contact and on reaching the contact on the adjustable pointer it completes the circuit through two terminals on the periphery of the indicator. The maximum current through these terminals and contacts should not exceed 20 milliamps on a non-inductive circuit for supply voltages up to 230 volts. When required for the control of larger currents a relay is used consisting of a coil actuated by the currents through the thermometer contacts operating on a tilting mercury switch suitable for interrupting the specified electrical load. If an audible signal is required upon the predetermined temperature being reached a three-terminal bell can be supplied for this purpose.

A bimetallic spiral strip or a corrugated metal expansion cylinder or bellows is commonly used in simple thermostats for the control of air temperatures in rooms, workshops, laboratories and industrial plant in general. One form of room thermostat is illustrated in Fig. 68 as made by The British Thermostat Co., Ltd., where control on the " on-off " principle is

obtained either through a mercury tube switch or a silver contact switch, with snap action in both cases, operating with a minimum differential varying from 2° F. to 5° F. according to the type and range, and a switch rating at 250 volts of 15 amps. a.c. or 10 amps. d.c. For more remote control the thermostat may be operated through a bulb and capillary tube. In a similar thermostat made by The Rheostatic Co., Ltd. the bimetallic strip controls a micro-gap contactor, and has an

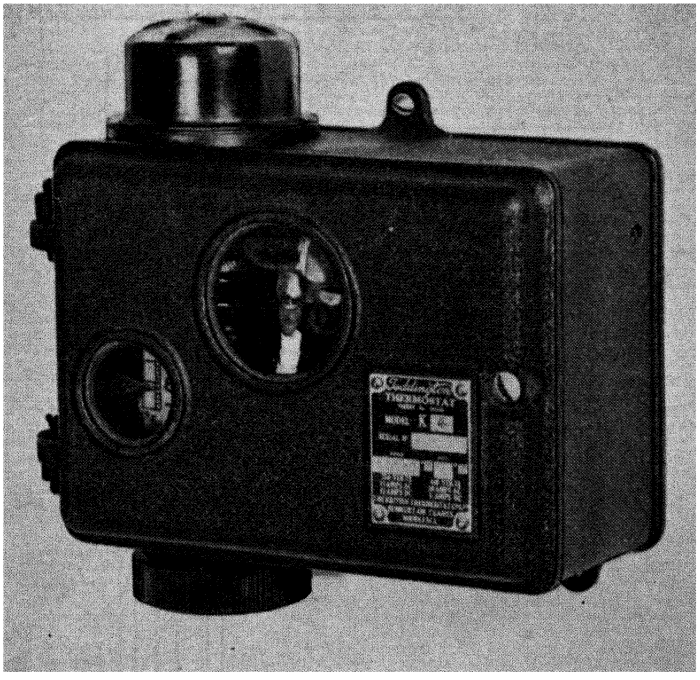


FIG. 68.—Room thermostat (Courtesy The British Thermostat Co Ltd).

accelerating electric heater, which comes into action when the thermostat calls for heat. This causes the heating device to supply the heat in shorter impulses. In important installations excessive cooling down of a furnace during an off-heat period may be avoided by having an automatically controlled flue damper. Also an extra contact may be provided for the thermostat accelerating heater to be cut out during a period of continual heating, as in the early morning after a lowered night temperature.

The same firm supply thermostats for the control of temperatures in electric ovens, immersion heaters, boilers, calorifiers, steam and water heating systems, and similar installations, depending for action upon the relative lengthwise expansion of a metal tube, of various nominal lengths up to about 18 in. controlling a micro-gap having heavy silver alloy contacts enclosed in the head. The operating principle of this

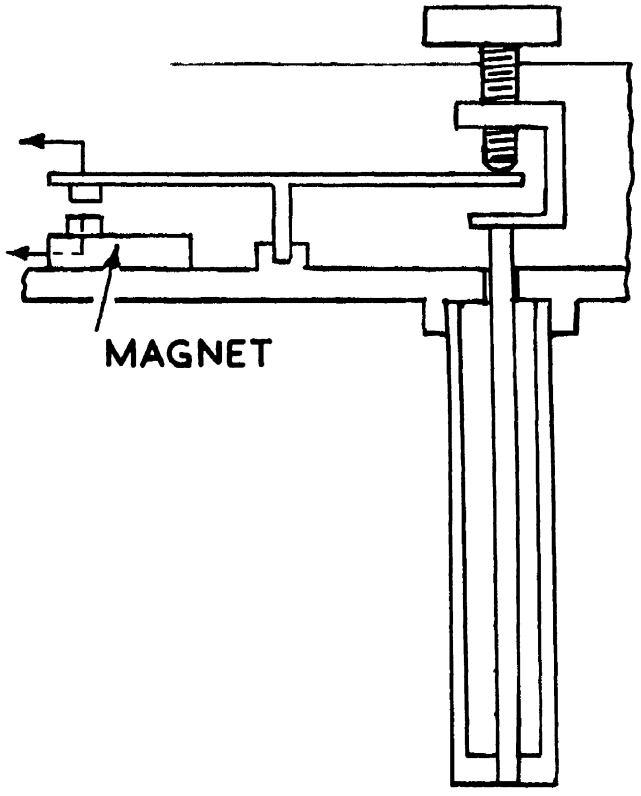


FIG 69.—Thermostat using expanding tube and rod

type of thermostat is represented in Fig. 69. The central rod has a lower coefficient of expansion than the tube so that, when the temperature of the tube rises, the relative lengthwise expansion between the tube and the rod causes the rod to depress the spring lever and thereby open the contacts. The temperature at which this occurs is determined by the screw adjustment shown. With contacts of relatively large area, and made of highly conductive metal such as silver, a fairly

high alternating current may be broken without serious burning of the contacts. The arc formed on breaking the contacts is rapidly extinguished as the alternating current momentarily passes through the zero value, due to the rapid conduction of the heat generated by the transient arc and the action of the magnet on the arc.

For small electric water heaters in domestic use the stem may consist of a brass tube enclosing a nickel steel rod. In electric cookers the tube may be of solid-drawn bronze, and an engraved knob in the head of the thermostat gives an adjustable temperature control between 200° F. and 550° F. The knob incorporates a pilot lamp which varies the intensity of the light emitted according to the setting, being brightest at the higher limit of 550° F. The lamp lights only when the oven heating elements are carrying current. Boiler thermostats have the stem of heavy-gauge brass and carry a calibrated knob on the enclosed head for adjustment of the temperature at which the micro-gap contacts open or close. They are available in two-contact form for the control of coal or oil burners, pumps or electric heating loads, and in three-contact form for the control of pulling motors or motorised valves. Some protection against the failure of the furnace flame in oil fired installations is sometimes required. The thermostat for this purpose is located in the flue or in the fire door. The stem is a tube of special steel alloy capable of withstanding temperatures up to 1000° F. The micro-gap switch may either shut the plant down directly on failure of the flame or may operate electric oil supply valves or central control panels.

The micro-gap switches are capable of making or breaking an a.c. current of 15 amps. on non-inductive loads up to 250 volts or of starting a single-phase a.c. motor of ½ h.p. at 200–250 volts controlling a fuel oil valve or gas valve, provided the starting current does not exceed 15 amps. For heavier loads relays or contactors are used where the thermostat contacts control a coil circuit in the contactor with a coil current up to 1 amp. a.c. at 250 volts or 0·1. amp. d.c. Positive opening of the contacts in the contactor when the coil circuit is broken is assisted by a wired device to destroy residual magnetism in the iron circuit. These a.c. contactors embody the micro-gap switch, thus ensuring that the energy of the arc when the

contacts break is reduced to a minimum. The special contact design provides a rolling action which reduces the possibility of the contacts welding together and allows them to make circuit on comparatively large inrush currents without damage. The d.c. contactors follow the same lines of construction but incorporate an electro-magnetic blow-out to ensure efficient arc extinction. The maximum continuous heating load is usually 30 amps. a.c. per pole with a maximum main circuit voltage of 440 volts, and a maximum inrush current of 100 amps. a.c. per pole.

It is now the usual practice in important heating plant to make the control of the boiler or heater fully automatic, except for particular conditions of failure to be described later,

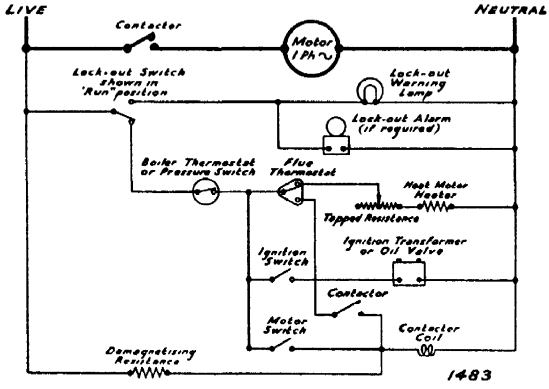


FIG. 70 —Automatic controlling system.

in which case it may be necessary to re-close the lock-out switch by hand to obtain a re-start. The circuit diagram in Fig. 70 represents one arrangement of the on-off type of burner control adopted by The Rheostatic Co., Ltd. The main operating parts are a hand-operated lock-out switch for starting, a boiler thermostat for water heating or a pressure-operated switch for steam heating, a flue thermostat, heat motor heater, ignition transformer, contactor coil to control the two contactors shown, and a single-phase motor operating the fuel oil pump or motorised valve. In the diagram the lock-out switch has been moved by hand to the starting or running position ; the boiler thermostat or other control arrangement is calling for heat supply to the boiler, and the flue thermostat has not yet moved from the " cold " position. This flue thermostat is specially

designed to suit automatic control and has a slipping clutch placed between the thermostat element and the contacts so that the thermostat can open the circuit of the heat motor heater for a definite rise of temperature, say 50° F., from the cold value, and after making the other contact, slipping occurs between the element and the contact position as the flue temperature continues to rise to its working value. Similarly, when the flue temperature falls by a similar amount, say 50° F., below the working value the circuit through the heat motor heater is again made. The heat motor heater in operation controls, through special thermostat switches, the lock-out switch and the ignition and motor switches. Under the conditions shown in the circuit diagram the heat motor heater is gradually heating up and in about $2\frac{1}{2}$ minutes from the start the heating effect operates a pilot switch which closes the ignition switch to operate the ignition transformer or gas pilot valve, and a few seconds later also closes the motor switch. This completes the circuit through the contactor coil which then electro-magnetically closes the two contactors and thereby starts the burner motor. In normal conditions the fuel ignites and the flue temperature rises, which causes the flue thermostat to move from the cold to the heated position, and this breaks the circuit of the heat motor heater. This heater then cools and allows the ignition and the motor switches to return to their normally open positions. The contactor coil circuit is now maintained through the "hot" contact position of the flue thermostat and the contactor poles. The burner will now operate until the boiler thermostat or other controlling device breaks the control circuit and thus shuts down the fuel supply. The next call for furnace heat brings the above cycle of events into operation again and so on.

If the fuel failed to ignite when the ignition device had been switched on as described above and the burner motor started, the flue thermostat would stay on the "cold" contact and therefore the heat motor heater would continue to operate. If there were no flame within approximately 45 seconds after the burner motor starts, the heat motor heater will operate the lock-out switch to isolate the control circuit so that the whole plant stops, and the switch completes the circuit to a warning lamp or other warning signal. The plant cannot be

re-started until the lock-out switch is re-set by hand by means of an external lever protruding through the cover of the controller box.

If the flame should fail when the plant is in operation the flue thermostat would cool down sufficiently to break the contactor coil circuit and thus cause the two contactors to open. This stops the burner motor, but, by returning thus to the " cold " contact the thermostat allows the starting cycle to come into operation again so that, after about the $2\frac{1}{2}$ minutes interval required for the heat motor heater to close the ignition and motor switches, the burner motor starts up again. Should the failure of the flame persist then the plant will be locked out by the action of the heat motor heater as described above. The delay period of $2\frac{1}{2}$ minutes gives the combustion chamber time to clear or purge itself of oil vapour or gases, and thus acts as a safeguard against an accidental explosion in the furnace or combustion chamber. If the flame failure has been due to a momentary blockage of the burner, the second attempt allows only a minimum loss of heat consistent with safety.

Should the electric supply fail, the control re-cycles in the normal manner when the supply is resumed. If the flue thermostat is deranged so that it remains in the cold position the plant will lock out. Complete safety is provided in the event of defective wiring, broken leads or earth faults.

This circuit arrangement gives great flexibility to the control system. The controlling instrument can be supplemented by other devices, if required. For instance, when heavy oils are being used an oil pre-heater may be necessary to reduce the viscosity and to improve the burning quality of the oil. The pre-heater can be wired in the circuit so that the burner cannot operate when the temperature of the oil is below the minimum working value.

This control system is suitable for the direct switching of single phase a.c. and d.c. motors up to 1 h.p., 200/250 volts, provided the starting current does not exceed 30 amps. A special control can be provided for direct switching of three-phase motors up to 4 h.p., 400/440 volts, if the starting current does not exceed 30 amps. per pole.

In some cases the modulating or proportional control system is to be preferred. The valve and control motor shown in

Fig. 71 was designed by The Rheostatic Co., Ltd., for the automatic proportional control of water or steam flow in accordance with the demand made by the controlling thermostat. The valve is available in five sizes up to 2 in. bore. Although it may be applied in any installation where proportional or modulated flow is required it has a particular application to the control of heating and cooling batteries in air conditioning and to other ducted systems, and to heating

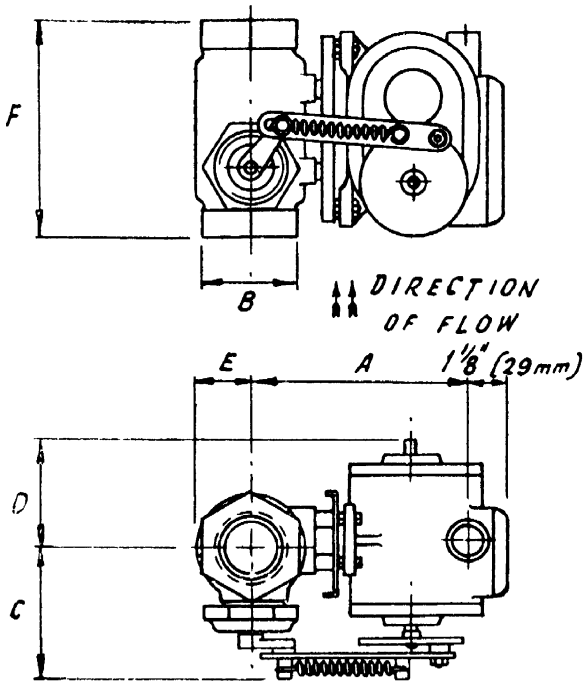


Fig 71 —Modulating valve

calorifiers of water to water, or steam to water, patterns, and it may be controlled by an outside " Pilot " thermostat or compensator, or by a duct or room thermostat according to arrangement. An idea of actual sizes of the valve and motor is given by dimension F, which varies from 6 in. for a ¾-in. bore valve to 9¼ in. for one of 2-in. bore.

The valve body is a bronze casting screwed at both ends with B.S.P. threads and is fitted with a packless gland. The valve spindle is connected by inside linkage to a carbon plunger so that the plunger moves co-axially inside the valve, covering

or opening V-shaped ports which allow the flow to be modulated in approximately a straight line relationship with the angular movement of the operating crank arm. The final closing movement of the valve brings the plunger to bed against an annular seat to give a tight shut-off. The motor is a low voltage a.c. motor provided with two stators, either of which can be energised at will by the controlling thermostat so that the motor can move in either direction or remain stationary at any point in its normal travel. The motor is connected by gearing to the operating crank connected by a link to the valve lever.

The movement of the valve motor is governed by the controlling thermostat through a timing device referred to as the " response regulator," which causes the motor to rotate in the appropriate direction in a series of impulses until the desired valve position is reached, sometimes referred to as " inching " the valve. This control of the rate of valve movement and change of flow of the controlled medium enables the controlling thermostat to follow as closely as possible to prevent hunting through over- or under-shooting of the temperatures.

The controlling thermostat has a " direction " switch with the two contacts 1 and 2 and a " speed " switch 3J, as indicated on the wiring diagram in Fig. 72. The direction switch can take up three positions corresponding to (1) " valve opening," open or " valve stationary " or (2) " valve closing." In Fig. 72 the direction switch is represented as at contact 2 and the speed switch 3J as open.

When the position of the modulating or proportional control valve is such that thermal balance has been attained with the thermostat satisfied, the direction switch in the thermostat will be in the open or " valve stationary " position, the speed switch will be open, and the valve will be stationary somewhere between fully closed and fully open according to the demands for heat. Within the temperature " differential " of the thermostat, say from 1° F. to 4° F. according to the arrangement, and referred to as the " neutral zone," the valve will remain stationary, but if the temperature varied beyond the limits of the neutral zone, the direction switch in the thermostat would move to its appropriate contact and the valve motor would be energised through the response regulator

and thus cause the valve to be moved towards the new position required to satisfy the changed temperature condition.

The " response regulator " consists essentially of a pair of switches which are continuously operated in sequence by a small synchronous motor and contact maker, and the valve motor is energised only when both of these switches are closed and as long as the controlling thermostat calls for a change in the supply of heat. The valve motor will therefore receive a series of impulses, closing the valve for the conditions represented in Fig. 72. The length of the impulses from the

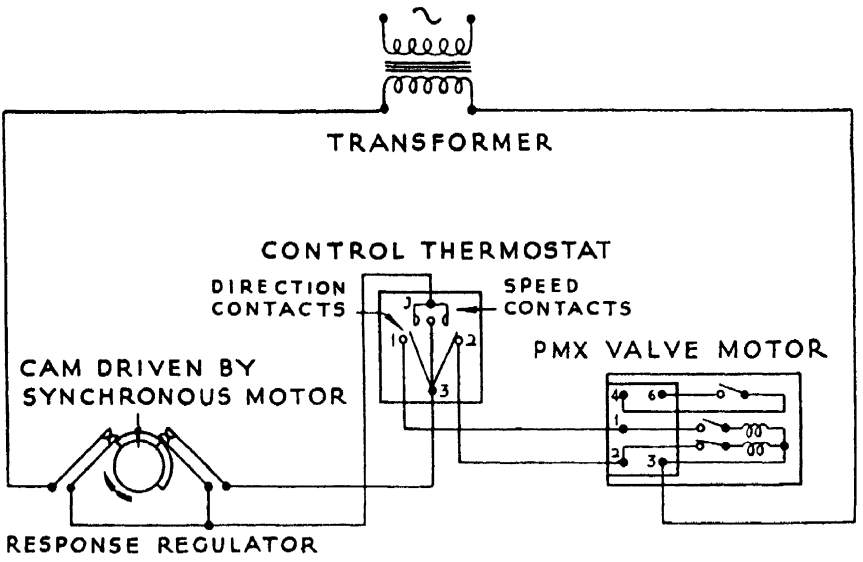


FIG. 72.—Response regulator control (The Rheostatic Co. Ltd.).

response regulator suited to different installations can be varied on site by altering the circumferential position of the right-hand switch to give impulses from 1 second to 10 seconds in each minute.

Should the demand for a change in the flow through the valve not be satisfied by the rate of response given by the direction switch of the thermostat, and the temperature difference become greater than that within the slow speed zone, the thermostat makes one or other of the speed contacts J and this will short-circuit the right-hand adjustable contact switch in the response regulator, thereby causing the valve to be moved at the rate of 30 seconds in each minute. As soon as the tem-

perature difference drops within the low speed zone, say 20° F., the speed contacts open and the operation of the valve then continues with the shorter impulses until the thermal balance is reached, when the thermostat switches will be open and the valve movement ceases.

Most makers of temperature controllers adopt similar arrangements of control with suitable modifications according to the degree of control required. Instead of making use of the flue thermostat some prefer an electrode system to respond instantaneously to flame conditions by employing the electrical conductivity of the flame itself, in virtue of the dissociation of the components of the fuel, or in other words, the splitting of the neutral particles or atoms making up the burning gases partly into positive and negative particles as long as the combustion proceeds. These particles have a strong tendency to recombine due to mutual attraction, and, should the combustion fail due to loss of ignition or by failure of the pilot or the main flames, these positive and negative parts instantly recombine and the conductivity disappears. The flame has a relatively high resistance, say from 2 to 8 ohms, and if the circuit is completed through a metal or ceramic electrode exposed to the flame the a.c. current may need to be amplified by electronic means to operate a relay in order to control the fuel supply. Oil or pulverised fuel and luminous gas or other extremely hot gases do not readily lend themselves to protection by the electrode system and for these conditions the Brown Instrument Co. and the Wheelco Instrument Co. have devised photo-cells as the sensing elements. The cell is fixed to the furnace and sighted on the flame in the same manner as is represented in Fig. 51, p. 111. The cell is chosen to be particularly responsive to wave-lengths emitted by the flame, but not to radiations from furnace walls, etc. The shutting down of the primary or the pilot fuel is effected through electronic amplification in the absence of flame, thus safeguarding the furnace against possible explosive conditions if the fuel supply continued in the absence of flame. In action the controller should be able to distinguish between unsafe firing conditions and the normal variations of combustion control, for nuisance shut-downs of the fuel supply may reduce the productive capacity of the plant, and may be liable to cause an

operator to devise ways of by-passing the safeguarding of the combustion system. The control system should be able to prevent an unsafe start if the recommended procedure at starting were not followed.

Flame conductivity in the combustion chamber may fail to operate in some cases because of an accidental insulation leakage, or short circuit, or the earthing of an electrode. In a new development * of the Honeywell system the property of flame rectification has been adopted. If suitable alternating current is applied either to the flame electrode inserted in the flame or to a suitable photocell sighted on the flame the resultant rectified current, after amplification, operates the relay system, and is available only when flame is present. The flame electrode type is generally used for non-luminous flames, such as gas flames, while the photocell type is generally used in luminous flames, as in oil flames. The relay provides about a three second interval from the time the flame goes out until it acts to shut off the fuel supply, and can detect flame in about 0·2 second. The system is approved by the Associated Factory Mutual Fire Insurance Companies and the Underwriters Laboratories, Inc.

The ventilation of rooms and buildings is usually associated with the problem of the heating and temperature control. In simple arrangements the hot-water or steam-heated radiators may be placed under the windows in each room with an outside grate opening behind each heater fitted with an adjustable shutter under hand control. It may be an advantage to the circulation of the air if suitable ducts are provided in the opposite walls leading to the outside. In more important installations motor-driven fans may be arranged to carry the air across the heated coils in the rooms, placed in the most convenient positions suitable for the particular case.

Where large numbers of people may have to be accommodated, as in large schools or colleges, public meeting halls, large offices or works, and the like, it is a normal practice to force the air through ducts to the various parts of the building by means of fans, and to provide the heating by forcing the air over steam- or water-heated coils on its way to each room, with

* "New Combustion Safeguard Equipment," by J. C. McCook, *Instrumentation*, No. 5, 1950.

thermostatic duct or room control. On this system the heating coils may be situated at ground level, and, in that case, if there are several stories of rooms to be heated and ventilated in this manner the upper rooms may tend to take too large a share of the heated air compared with that taken by the lower rooms due to the greater chimney action of the heated air in the shafts leading to the upper rooms.

In large towns or in industrial districts the "fresh" air supply to large buildings may be filtered or washed before reaching the fans, and in some cases the air supply may be humidified or dehumidified under automatic control. The system providing heat supply in winter can be adapted to provide automatic cooling in summer. Such elaboration of control would probably be more effective in climates subject to hot summers with cold winters than in more temperate regions. Details of these systems of control would be outside the scope of the present work. Particulars of various modern systems in this and other directions is to be found in the publication "Instrumentation" issued periodically by and through Messrs. Honeywell-Brown Ltd., of Middlesex.

When a thermocouple is used as the temperature-sensitive or detecting element some makers of controllers utilise the potentiometer principle, or with resistance thermometers, the Wheatstone bridge arrangement. The controlled heating device, whether an electrical resistance, or a gas, oil or steam valve, may be operated electrically through the out-of-balance effect on a sensitive galvanometer when the temperature is above or below the selected control value. In one arrangement adopted by the Cambridge Instrument Co., Ltd., for instance, the galvanometer forms the sensitive detecting unit. The "balanced" or "null" position of the galvanometer pointer is adjusted by a rheostat in the potentiometer or Wheatstone bridge circuit to correspond with the temperature shown on the scale at which the adjustable control temperature is desired. Deviation from this control value results in the tilting of a mercury switch, thus making or breaking the electric supply. Normally this mercury control switch is rated at 10 amps., but switches suitable for breaking circuits up to 30 amps. can be supplied. The switch may be arranged with two contacts to make and break the circuit of an electric fur-

nace directly where the load is relatively small, or to actuate an auxiliary relay or contactor where the load is large. Three contacts may be arranged to close one circuit when the temperature is low and another circuit when the temperature is above the control value, using a common centre connection. The controller can be arranged to control three separate zones of temperature by means of a three-zone distributor operated by the driving motor of the controller to give a complete cycle in 21 seconds. The temperature for each zone is set independently on one of three calibrated dials.

Standard ranges of control with different thermocouples are shown below, but the scales can be "set up" to any suitable range dependent on the type of couple used. The accuracy of control obtainable is of the order of $\pm 0{\cdot}1\%$ of the full scale. Corresponding ranges in deg Fahr. are available.

Iron-Constantan	*Titan*	*Platinum-Rhodium*
0–300° C.	0– 800° C.	0–1400° C.
0–600° C.	0–1000° C.	
0–800° C.	0–1200° C.	

For process work the controller may be arranged to adjust the control temperature according to a prearranged time-temperature curve by incorporating a suitably formed cam to give this adjustment at a speed of one revolution in any convenient period up to 96 hours.

When thermocouples are used an automatic cold junction compensator is supplied, and, if desired, a broken thermo-junction device can be incorporated which switches off the furnace if the thermocouple circuit is broken. Any convenient length of connecting lead can be used without affecting the accuracy. The current for the potentiometer circuit is supplied by a dry cell which normally lasts for about a year and usually needs to be standardised only once in 24 hours by comparison with a standard cell. If desired, automatically operated standardisation can be fitted.

Some makers of controllers use the same automatic mechanism to operate the indicator pointer or the recorder pen whether or not a controller is also installed. In the Leeds and Northrup Co. arrangement of the Wheatstone bridge for resistance thermometers represented in Fig. 19, p. 48, for instance, the slide wire contacts X and K are operated automatically by

the mechanism actuating the controlled heating device, or the similar contact X in the potentiometer arrangement when a thermocouple is used, shown in Fig. 32, p. 73. In both cases the position of the contact X represents on the scale the indicated or the recorded temperature. In a simple arrangement where the indicator is balanced manually the slide wire contact X is moved by hand until the galvanometer pointer comes to the zero or null position, and this balancing position of X indicates the temperature. To do this automatically for the indicator, recorder or controller requires some mechanism which is able to " feel " when the galvanometer needle deflects in either direction from the null position due to a lack of balance. In the Leeds and Northrup arrangement the galvanometer needle is free to take up its true position, but at short intervals of time a cushioned clamp grips the needle and immediately

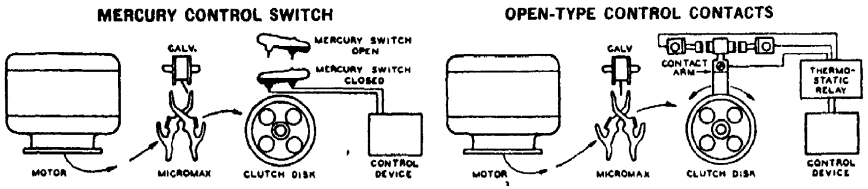


FIG. 73 —Controller mechanism (Leeds & Northrup Co)

a pair of cam-operated setting levers close on the needle. If the temperature is unchanged the needle would be found to be in the zero or null position and the setting levers closing on this position finds the undeflected needle at zero, and the balancing mechanism does not act. With a change of temperature, however, the system becomes electrically unbalanced and the needle deflects accordingly. In moving to an off-centre position the levers have tilted a clutch arm which now clamps to a clutch disc, and, through the operation of a cam, the clutch disc turns and with it the slide wire contact is moved to rebalance the system.

In a controller of this type equipped with a mercury switch the switch may be single-throw to control the power supply or double-throw to operate a two-position or " on-off " valve mechanism. The switch is mounted on the clutch disc shaft and in tilting one way or the other makes or breaks contact to operate the external control device or to control a small elec-

trical input directly. Clutch stops prevent the switch from tilting too far. This arrangement is represented diagrammatically in Fig. 73. If the controller has open type contacts, as represented in Fig. 73, the contact arm turns with the clutch disc and moves from its open centre position one way or the other, thus making either high or low contact to actuate a

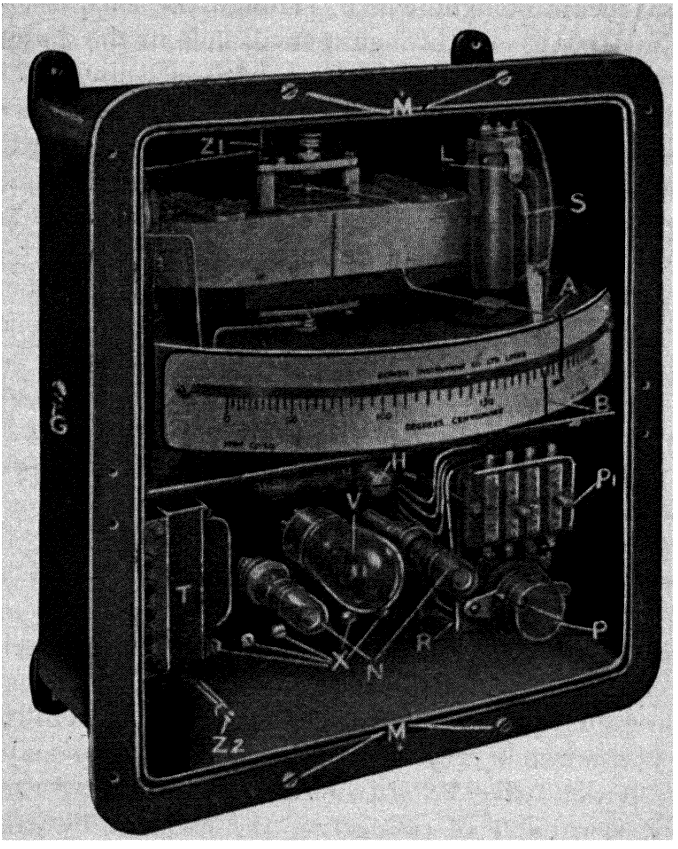


FIG. 74.—Controller arrangement (Bowen Instrument Co., Ltd.).

thermostatic relay, which in turn operates the external control device. After each contact the arm returns at once to its open position, ready to respond in either direction to the next movement of the clutch disc.

The main features of an electrical temperature controller built by the Bowen Instrument Co., Ltd., of Leeds is shown in Fig. 74, with the upper and lower covers removed. The galvanometer needle A is free to move over the indicator scale

in accordance with the ordinary practice in temperature indicators. A swivelling frame carries an optical system consisting of a small lamp L, a lens, a diaphragm, and a selenium bridge or cell inside a glass bulb. By means of the shaft H this system can be moved round to any desired position of temperature control shown by a red index B on the scale. The lamp L projects a beam of light which, through the lens, is focussed to a point as it passes through a small hole in the diaphragm, afterwards spreading out and falling on the selenium cell. The cell is used to alter the grid bias of an ordinary thermionic valve so that when the light from the lamp L falls on the cell there is no anode current through the valve, but as soon as the beam of light is obscured the anode current flows to actuate the relay R so as to reduce the supply of heat. The beam of light is obscured when the indicator needle reaches the small hole in the diaphragm aforementioned. In consequence the line of action of the relay between "fuel or heat on or off" is very sensitive. The relay R is actuated by a current of a few milliamperes while it controls a circuit load of 1 kw.

The primary winding of the transformer T is tapped for a.c. mains supply ranging from 200 to 250 volts, or other voltages to order. The several secondary windings in this transformer provide the necessary voltages for the power valve V, the projector lamp L, and for the red and green signal lamps N. An adjustable potential divider P in the selenium cell circuit is available should the relay R be sluggish in action in either direction, but it should be used carefully as its setting is somewhat critical, and an excess setting may overload the power valve V. In small electric furnaces the relay switch R is capable of connecting the main or by-pass load current to the furnace directly, but for large electric furnaces the relay is arranged to operate a cut-out switch of the required capacity. Similar controls on the motor- or solenoid-operated valves regulate the temperature of gas-, oil- or steam-heated plant. It is thus seen that there are no mechanical contacts between the pointer and the relay.

The pyrometer circuit may be opened by turning the switch Z_2 anti-clockwise by means of a screw-driver. The corrector Z_1 is then used to adjust the pointer A to the correct cold junction temperature. The screw Z_2 is then turned clockwise to

re-connect the pyrometer circuit. A calibrator screw G is provided for correcting the temperature reading if necessary. In a horizontal line below the valve V are eight marked terminal screws for the external connections.

The Wheelco Instruments Co. of Chicago, U.S.A., and their associate company Ether-Wheelco Ltd. of Birmingham, have developed a system whereby the galvanometer or indicator operates through an electronic system on a relay which in turn controls the fuel or heat supply valve. The system is represented in Fig. 75. The sensitive indicator has the coil 3 supported in two sapphire bearings and moves in the field of an Alnico V magnet. In Fig. 75 the indicator is shown to be

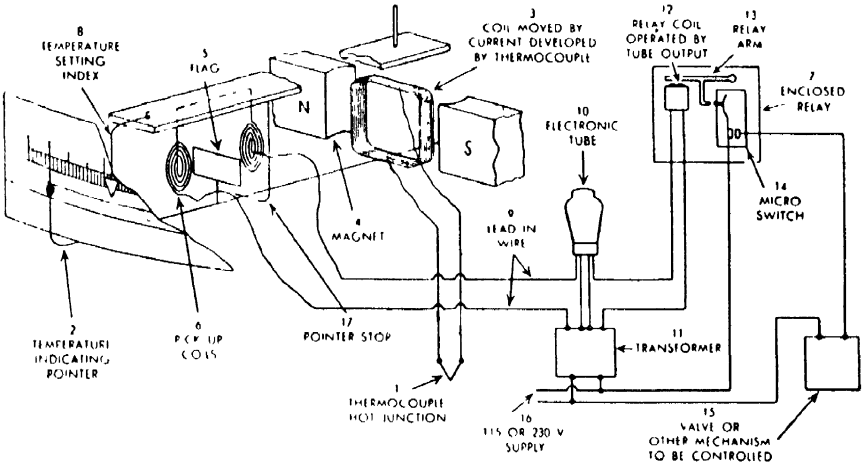


FIG 75.—Controller system (Wheelco Instruments Co.)

acted on in the usual way according to the temperature and type of thermocouple, and the same effect may be obtained from an unbalanced resistance coil or bulb. The indicator pointer 2 carries an aluminium flag 5 which is in the inductive field of the two pick-up coils 6 fixed to the temperature setting index 8. These coils are in the high frequency electronic oscillating circuit of the valves or tubes 10, and the flag varies the inductance according to position and thereby causes a change in the oscillatory energy of the circuit. The electronic valve or tube 10 is thus capable of altering the flow of current through the relay coil 12 which controls the armature 13 and the position of the contacts 14 to determine the opening or closing of the valve or other mechanism 15 to be controlled.

A movement of the indicator pointer of only 0·006 in. is capable of producing control action. The controller described gives two-position control, that is, " high-low " or " on-off " control, but the system can be also arranged to give multi-point and proportional control according to requirements. The various units in the controller are arranged to be plugged in, thus eliminating the need for separate wiring. Compensation is made for the ambient temperature of the indicator, and with thermocouples a cold junction compensating spiral is incorporated. It is seen that mechanically operated contacts are not needed between the indicator pointer and the relay on this system.

The recorders are operated on a similar system except that the coils 6 are mounted on a follow-up arm with an alignment index, and this is coupled to the recorder pen or scriber mechanism through gears driven by the operating control motor. When the alignment index and indicating pointer are in exact coincidence the output of the oscillating circuit is balanced with the supply voltage and the driving motor remains stationary. The control index determines the positions of roller type snap action switches. When the indicating pointer crosses this pre-set control index the control action takes place.

Electronic circuits are used in some systems to produce an automatic balance in a potentiometer or Wheatstone bridge circuit without using a galvanometer to show the out-of-balance effect. The out-of-balance current itself, magnified by electronic means, is used as the sensitive unit, and the same system may be adopted whether the purpose is to indicate or record or to control the temperature. An out-of-balance voltage of not more than $\frac{1}{10}$ millivolt in a thermocouple for instance, perhaps equivalent to a change of a few degrees in temperature, may be amplified in voltage and power until it is capable of restoring the electrical balance, and of operating a motor to move the indicator pointer, or the pen of the recorder, and to operate the controlling arrangements for an electrically heated, or a gas- or oil-heated, furnace. Instead of amplifying directly such a small out-of-balance direct current most electronic circuit designers preferred to convert the d.c. signal into an a.c. or rapidly changing signal because this was

more readily amplified. A detailed description of one such system will illustrate the general scheme.

The line circuit diagram * shown in Fig. 76 illustrates one continuous balance system used by Messrs. Honeywell-Brown Ltd. of London, an associate of the Brown Instrument Co. of Philadelphia, Pa., U.S.A., in their " Electronik " potentiometers. The hot thermojunction is in circuit with a finely divided potentiometer slide wire. This slide wire is shown here arranged in a straight line form though actually it may be a dual wound coil on a circular ceramic former, with 1600

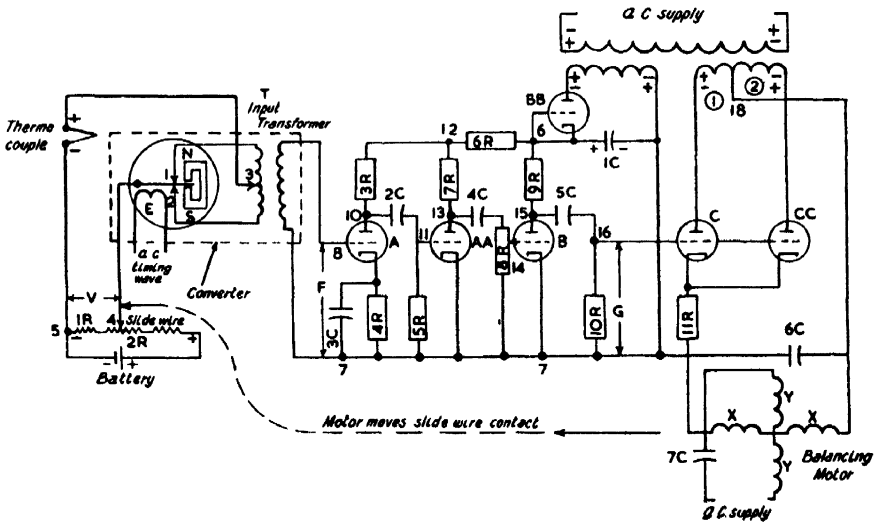


FIG 76 —Controller system (Brown Instrument Co) From *Electronics in Industry* by G M Chute

convolutions, totally enclosed and immersed in oil. The potentiometer circuit is completed through one or other of the contact points 1 or 2 and the central contact 3 in the primary of the input transformer T. When the voltage V balances that of the thermocouple the balancing motor remains stationary, but any lack of balance causes the motor to turn in the required direction to restore the balance by moving the slide wire contact 4, from which the indication or recording of the temperature is obtained. At the same time the motor operates the control of the supply of heat at the furnace or similar plant if a controller is installed.

* From *Electronics in Industry*, by G. M. Chute. Copyright, 1946. Courtesy of McGraw-Hill Book Co.

To describe the action in greater detail, an energising coil E is supplied with alternating current from the a.c. supply line through a small step-down transformer, and causes a metal reed of what is called the " converter " to vibrate at the standard

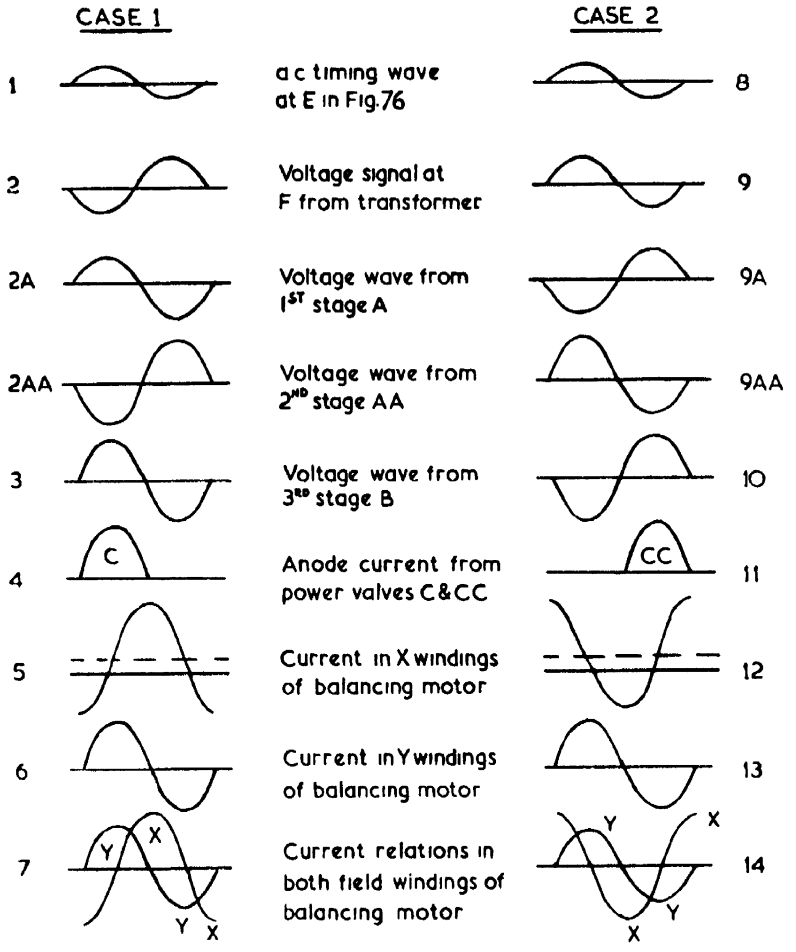


FIG 77.—Voltage or current variations in controller From *Electronics in Industry* by G. M. Chute. Copyright 1946. Courtesy of McGraw-Hill Book Co.

supply rate in the magnetic field of a permanent magnet. This causes the reed to make contact with the contact points 1 and 2 alternately. The metal reed touches the upper contact 1 during each positive half-cycle of the a.c. power supply due to this half-cycle magnetising the reed so that its right-hand end is a South pole and is therefore attracted to the North pole

of the permanent magnet. In the same manner the reed makes contact with the point 2 during the negative half-cycle. To explain the action suppose a rise of temperature were to occur, then the e.m.f. of the thermocouple would rise and thus become greater than the voltage V across the points 5 and 4. Electrons would then be caused to flow from 5 to 4 through the resistance 1R and part of 2R to the slider contact 4 and thus to the contacts 1 or 2 and to the central contact 3 of the transformer T. This transformer is therefore subjected to an alternating voltage at line frequency as represented by the curves 1 or 8 in Fig. 77,* and this induces a corresponding a.c. voltage across the secondary winding at F in phase nearly with the line voltage, and represented by curve 9 in Fig. 77, but not necessarily having the same voltage scale as in curve 8. This voltage is impressed on the grid of the first triode valve A and then becomes amplified in voltage and in power, as afterwards explained, causing the motor to rotate clockwise, say, and to move the slider 4 towards the right until the voltage V balances the thermocouple voltage, when the impressed voltage across F becomes zero and the motor stops.

If the temperature now falls for any reason the voltage V becomes too great and this causes an electron flow away from the mid-tap 3 and the transformer primary T out of the contacts 1 and 2 towards the slider 4. The resulting voltage produced at F is now nearly 180° out of phase with the timing wave 1 or 8, and is represented by the curve 2 in Fig. 77. After amplification this causes the motor to turn anti-clockwise and to move the slider 4 to the left until a balance is again attained.

The amplifier circuit is shown in Fig. 76. The input signal at F is the a.c. voltage wave, curves 2 or 9 in Fig. 77 as described above, and acts on the grid of the valve A. Three twin triode valves or tubes are used in the amplifier and are shown as six separate circles, with resistance-capacity coupling. The circles A and AA represent separate valves in the same valve enclosure, while B and BB represent another similar twin triode. The one triode BB acts as a diode rectifier to furnish d.c. voltage between the points or connections 6 and 7, filtered by

* From *Electronics in Industry*, by G. M. Chute. Copyright, 1946. Courtesy of McGraw-Hill Book Co.

the condenser or capacitor 1C. The anodes of A, AA and B receive the d.c. voltage from this supply. The twin triode valve C and CC acts as a power amplifier. Actually two twin triodes are provided, but work in parallel to increase the power.

Before attempting to explain in further detail the action of these circuits a short capitulation of the functions of the parts of simple thermionic valves or tubes may not be out of place. The simplest valve is the diode represented in Fig. 78. The cathode may be a heated filament or a plate indirectly heated by a filament. The anode is a plate subject to a potential in relation to that of the cathode, and the combination is enclosed in a vacuum tube. The heated cathode gives out electrons which are attracted to the anode when the anode has a

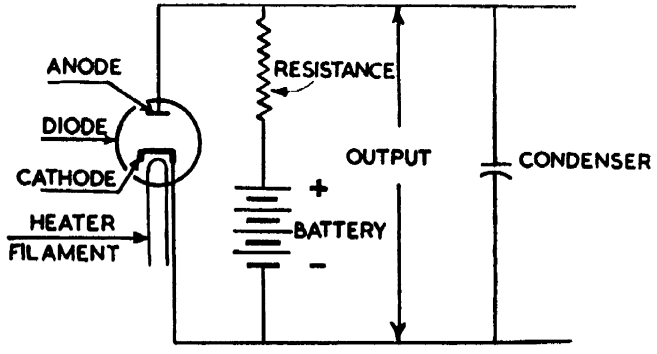


FIG 78.—Diode valve or tube.

positive potential, and these electrons find a path back to the cathode through the anode resistance and battery, which thus constitutes an anode or plate current. The direction of the flow of electrons is thus opposite to the conventional direction of current flow, the latter having been arbitrarily assumed long before the electron theory was founded. If the anode were subjected to a small negative potential the free electrons around the heated cathode would be forced back to the cathode by the action of the repulsion of charges of like sign, and no anode current would flow. Therefore if the anode is subjected to an alternating voltage making the anode voltage alternately positive and negative relatively to the cathode, the anode current will flow in one direction only, or, in other words, the original current has been rectified, and diode valves or tubes used in this manner are said to be half-wave rectifiers. In

general the output from the rectifier is fed into a "filter" circuit usually composed of condensers and impedances or resistances. A single condenser of suitable capacity placed across the output as in Fig. 78 is charged when the anode current flows through the diode and discharges through the load when no anode current is flowing, or when the output voltage falls below the condenser voltage, and thus gives a smoothing-out effect to the direct current in the manner represented by the dotted curve in Fig. 79. Thus diodes may be useful in an electronic system to obtain d.c. voltage or current when the system operates from an a.c. supply.

The triode valve has a third electrode called a grid, as at 8 in the valve A in Fig. 76, and is a metallic mesh placed between the cathode and the anode, but usually much nearer to the

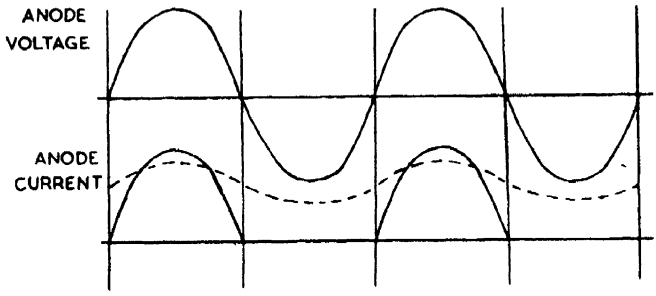


FIG 79 —Voltage and current variations from diode valve

cathode than to the anode. The grid operates to retard or to accelerate the flow of electrons between the cathode and the anode depending on the grid potential (grid bias) and in this way serves to control or vary the anode current. If the combination of grid signal and grid bias is highly negative in respect to the cathode no anode current will flow unless the anode voltage is very high but when the grid is made less negative or more positive the anode current increases. Because the grid is placed much nearer to the cathode than to the anode, variations of grid voltage are more effective than those of the anode voltage in changing the anode current.

Amplifier valves or tubes are of two types according to use, namely, voltage amplifiers to develop greater voltage output than is applied to the grid, and power amplifiers designed to develop an appreciable power output for little power input at the grid.

It is usually necessary to use more than one stage of voltage amplification. Three stages A, AA, and B are shown in Fig. 76 where the variation in the anode voltage output of A at 10 is impressed on the grid of AA at 11 through the condenser 2C, and again from the anode of AA at 13 on the grid 14 of B through the condenser 4C and the potential divider 8R. This divider permits operating adjustments of the balancing system to be made.

In considering the action of the valves A, AA and B it may be observed that, with a sinusoidal input voltage at the grid of each, then the potential difference across the load resistances 3R, or 7R, or 9R respectively are out of phase with that applied to each grid by 180 degrees, which may be more evident from the following reasoning. If the grid voltage becomes more negative the anode current falls off and the potential difference across the load resistance is reduced, with the result that the anode voltage becomes more positive. The forms of the voltage waves obtained are represented as 2A, 2AA and 3, and 9A, 9AA and 10 in Fig. 77 without paying particular regard to the scales of these voltage curves. It is the voltage wave 3 or 10 which is impressed on the grids of the power valves C and CC when the thermocouple voltage and the voltage V in Fig. 76 are out of balance.

The grids of the duo-triode valves, C and CC, are all in parallel. The anode voltage of C is obtained from the a.c. supply voltage through the winding (1) of the power transformer and that of CC through the winding (2), and in this way these anode voltages are made alternately positive and negative with the same frequency as the a.c. supply. If it is assumed that the transformer polarities have the upper signs marked in Fig. 76 for the positive half-cycle of the line voltage, the anode of C would have a positive voltage and of CC a negative voltage during this period. This means that CC could not have an anode current in this period whatever may be the grid voltage. The existence and magnitude of the anode current in C, however, would depend upon the potential of the grid during this positive half-cycle period. During the negative half-cycle of the line voltage the transformer polarities in the windings (1) and (2) would be reversed, thus impressing a positive potential on the anode of CC and a negative potential

on the anode of C, which action thus permits CC only to conduct anode current during this negative half-cycle. Thus the existence and magnitude of the anode current in CC depends upon the grid potential during this negative half-cycle. The anode currents in C and CC are represented in the curves 4 and 11 respectively.

There are three cases to consider. *Case* 1, when the input signal to the grids of C and CC is in phase with the line voltage (curve (3) in Fig. 77). *Case* 2, when the input signal to the grids of C and CC is 180 degrees out of phase (curve (10) in Fig. 77), and *Case* 3, when there is no input signal to these grids, that is, when the thermocouple voltage is in balance with V at the slider 4 in Fig. 76.

In Case 1, therefore, during the positive half-cycle of the line voltage, the anode of C has a positive voltage and the grid voltage is positive, which gives the anode current in C represented by the curve (4) in Fig. 77. During the negative half-cycle of the line voltage, while the anode of CC is positive, that of the grid is negative, and no anode current is obtained from CC.

In Case 2, the controlling effect of the grid for each half-cycle of the supply voltage has been reversed with the result that an anode current is obtained from CC during the negative half-cycle of the supply line, and nothing from the valve C. This is represented by the curve (11) in Fig. 77.

These anode currents (curve (4) for Case 1 and curve (11) for Case 2) are impressed as impulses on the stator windings XX of the balancing motor, and on the condenser 6C in Fig. 76 of suitable capacity, and induce an impulsive current in these stator windings XX, with a lag of 90° in Case 1 in relation to the mains supply, as represented in curve (5), and an advance of 90° on the mains supply, as represented in curve (12) for Case 2. Curves (6) and (13) represent the currents in the stator windings YY of the motor from the a.c. supply main. Since this winding YY constitutes an inductive circuit the current would lag behind the voltage were it not for the condenser or capacitor 7C of suitable capacity, which is introduced so as to induce a resonant current in the YY windings in phase with the main line voltage. The combined curves of current in the two windings are represented in Fig. 77 as (7) for Case 1 and (14) for Case 2.

The conditions in Case 3 create a constant potential on the grids of the valves C and CC at some negative value determined by the grid bias. The anode currents induced in both valves are equal on each of their half-cycle periods of operation and thus no impulse is impressed on the stator windings XX.

The alternating currents in the stator windings XX and YY at right angles create in the balancing motor two alternating magnetic fields at right angles, and the resultant of these two fields is a rotating magnetic field, rotating clockwise for one case of out-of-balance and anti-clockwise for the other case, and therefore exert a corresponding force or torque on the armature windings of the motor. The rotation of the motor then moves the slider 4 in Fig. 76 to restore the balance, and indicates by a pointer the corresponding temperature, or records it by an inking pen on the recorder chart. The controller also obtains its operating action on the controlled device or mechanism from the motor. When the new balance is obtained the alternating current and magnetic field in the stator windings XX cease to operate and the motor stops, since the alternating current and magnetic field in the stator windings YY alone has no turning effect on the motor armature.

The method of standardising the drop of voltage across the slide wire due to the dry battery is not shown in Fig. 76, but it is obtained on the principles represented in Fig. 77, p. 160, by comparison with the voltage from a standard cell. Instead of the manual operation of switches and resistances, however, in some models a push-button operation switches the standard cell into the circuit with suitable resistances in place of the thermocouple or other measured voltage, thus allowing the action of the balancing motor to readjust the battery rheostat to the correct position. This may be done at convenient times. In other models, usually when the recorder is of the strip type, this standardisation is carried out automatically every 30 minutes or so, as may be arranged, where the push-button action occurs automatically from the motor driving the chart.

There are many cases in industry where the manual push-button system of standardisation is sufficient for the purpose, although a small motion of the instrument pen or pointer

may occur during the brief interval of about 6 seconds due to standardisation. The exact amount of this motion may depend upon the length of time between standardisations, the condition of the battery, and changes of the ambient temperature. Where wide range instruments and on-off or wide-band proportional controls are used the consequences of these small pen motions on the controlling action of the controller is usually negligible.

With the increased use of potentiometer controllers in industrial practice, narrower tolerances in product specifications has led to the development of narrow range instruments for use with the more refined modes of control. In a few cases the control is even further refined with the addition of "rate response," whereby an initially large corrective action is obtained with a small change in the variable. In such control installations the pen motion during standardisation, whether manual or automatic, may be reflected in the control action to an undesirable extent. For those processes requiring very close control it may be desirable to have two separate balancing motors, one for the measuring circuit and the other for the standardising rheostat. To eliminate possible inductive action between the two motors, which might cause false control action in a controller, the two motor circuits are connected in a series to the amplifier output, and one or other of the motors is de-energised by shorting it with a mercury switch contact.

The balancing motor may be arranged to exercise control by any one of the methods described briefly on pp. 128–30. If the control is on the proportional system the adjustment of the controlled condition (heat supply in this case) may be obtained through two 135-ohm adjustable rheostats and a sensitive relay, arranged as a resistance bridge to control the position of a proportioning motor, as represented in diagram form in Fig. 80. The transformer is arranged to reduce the voltage to 20 to 24 volts a.c. The 135-ohm resistor HL has a slide centred at C under the control of the balancing motor previously described, which means that the slide is placed in a position in proportion to the deviation from the set point or desired temperature. If the bridge is in balance and the detecting element (temperature) changes, the balancing

motor moves the slide C proportionally towards H or L according to whether the temperature rises or falls. This causes the bridge to be out of balance, and the resulting out-of-balance current acts on the relay to make contact with the terminals 3 or 4 as the case may be, thereby operating on the proportional motor to close or open the controlled device or valve. This motor is also connected to the slide R of the 135-ohm resistor BW and moves the slide R to cut out a resistance similar to that put into the circuit by the movement of the slide C, and the proportioning motor then stops. Thus the proportioning motor assumes a definite position in proportion to the deviation of the detecting element from the desired or set valve. The

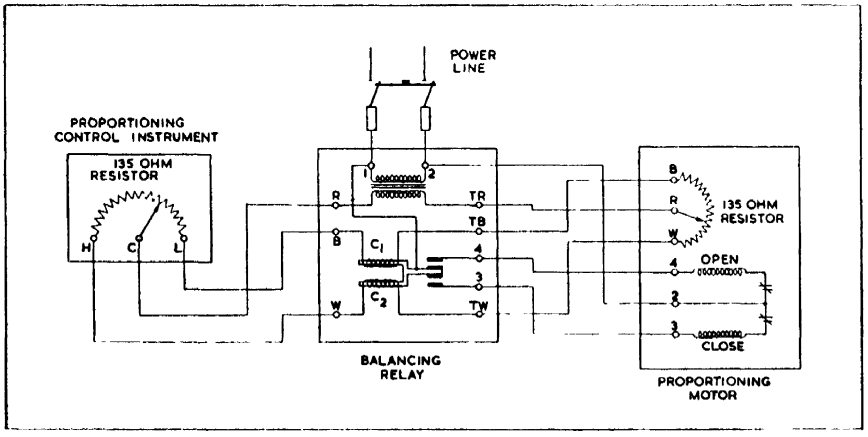


FIG 80.—Proportional control circuit (Brown Instrument Co).

proportional band between no heat supply and full heat supply is usually about 5% of the scale range of the indicator or recorder, and it is evident that the new balance does not necessarily give quite the same temperature as the previous point of balance. In important installations it may be desirable to be able to " re-set " the detecting element at the desired value, which may be done by hand in some cases, and in other cases automatically, by suitable alterations in the relay action. The same balancing and controlling system is available for measuring and adjusting the out-of-balance effect in resistance thermometers using the Wheatstone bridge principle.

A new Brown electronic balancing relay system has recently been developed for the proportional control arrangements, providing higher sensitivity. The new circuits are represented

in Fig. 81 and include the proportional control instrument actuated by the pen shaft, and the proportional motor resistor, as before. The desired function of the system is accomplished by electronic detection and amplification of the unbalance between the two opposing bridge circuits, which causes the mechanical relay contacts to operate in controlling the power supply to the " open " or " close " drive windings of the motor, and this also operates to restore the bridge balance contact, and the relay then cuts off the power to the motor. On the circuit diagram in Fig. 81 are also shown three additional slide wires. One is the proportional band adjustment in the instrument bridge which varies the voltage applied to this

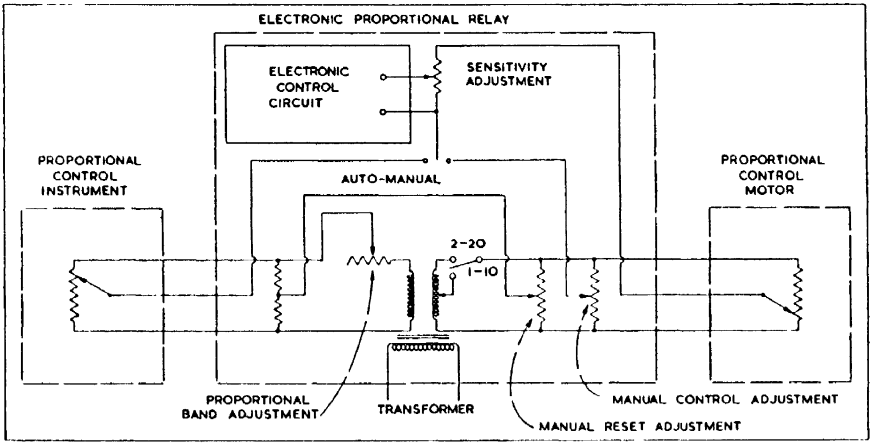


FIG. 81 —Electronic proportional relay circuit (Brown Instrument Co).

bridge, a higher voltage resulting in a narrower band. It will be noted that a single-pole double-throw switch marked " 2–20 " and " 1–10 " is provided in the relay. The figures refer to the range of adjustment in per cent of the instrument scale. The manual reset adjustment is used to bring the control motor to reset the control temperature to the selected value. When required, the manual positioning of the control motor is obtained through a switch marked auto-manual which disconnects the instrument bridge and connects the manual control slide wire in the motor bridge circuit. This motor position is then dictated by the manually adjusted slider. A sensitivity setting is provided, which adjustment depends upon the number of windings on the proportional resistor and upon

the amount of motor overrun or coasting due to inertia or delayed action after power is cut off by the relay. In order to take full advantage of the increased sensitivity of the electronic relay a 1000-ohm resistor is now supplied. A design is available with 100- to 135-ohm resistors for use in instruments already installed. Various other modifications are also available.

Similar purpose controllers working on the potentiometric system are built by Thermocontrol Installations Co., Ltd., of London, in association with Regulator and Instrument Ab Billman, of Stockholm. Among the several systems of zone controls this control may be provided by dampers of the louvre type, formed of aluminium blades of aerofoil section, controlling the air supply through the action of modulating or proportioning motors.

The Brown Instrument Co. have also developed various modifications of a pneumatic system of control under the title of " Air-O-Line " control, having, where necessary, an adjustable automatic " re-set " and an adjustable " throttle range." The pneumatic system operates through the deviation of the pointer or slide 4 in Fig. 76 from the selected value of the temperature.

Electronic amplification of the out-of-balance effect of the varying temperature of the resistance thermometer arranged on the Wheatstone bridge principle has been adopted by The Bristol Co., of Waterbury, Connecticut, U.S.A., and the associated company, Bristol Instrument Co., Ltd., of London. The scheme of this " Dynamaster " arrangement is represented in Fig. 82. The resistance thermometer T has the three-lead method of compensation, previously described on p. 47. A step-down transformer from the line supply provides a.c. current at 9 volts to the Wheatsone bridge. If the resistances R_1, R_2 R_3 and T happen to be out of balance an alternating voltage is amplified into a corresponding alternating current applied to one field or stator winding of the two-phase motor, while the other field winding is supplied continuously with a.c. current from the line supply. The resulting rotating magnetic field turns the motor one way or the other, as previously described on p. 166, depending on which side of the Wheatstone bridge is out of balance. The motor moves the

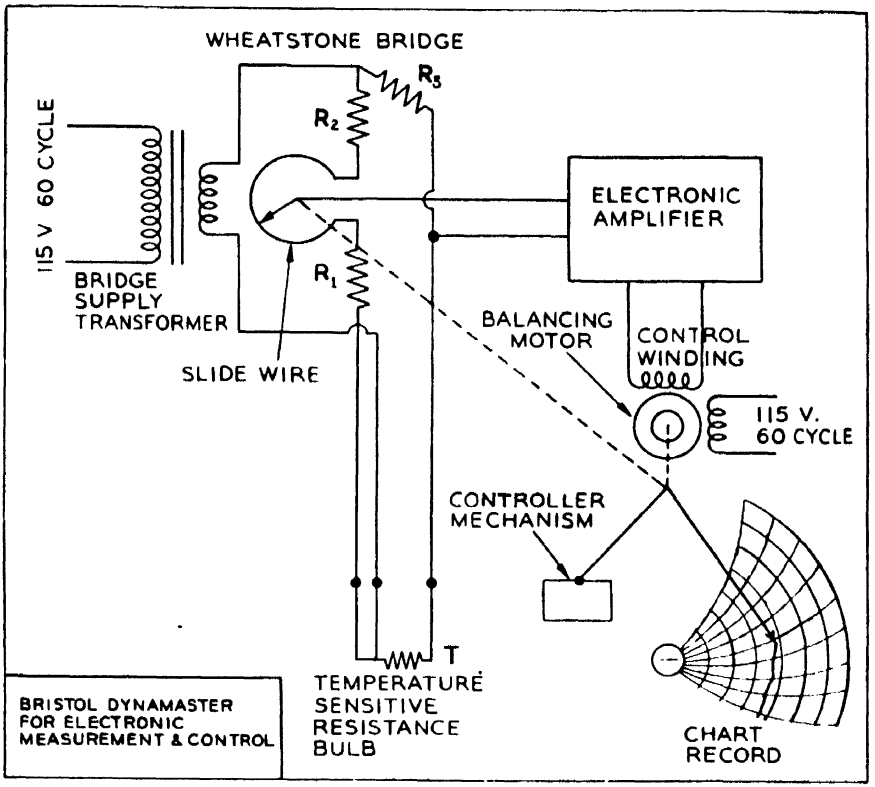


FIG 82 —Scheme of controller system (Bristol Co)

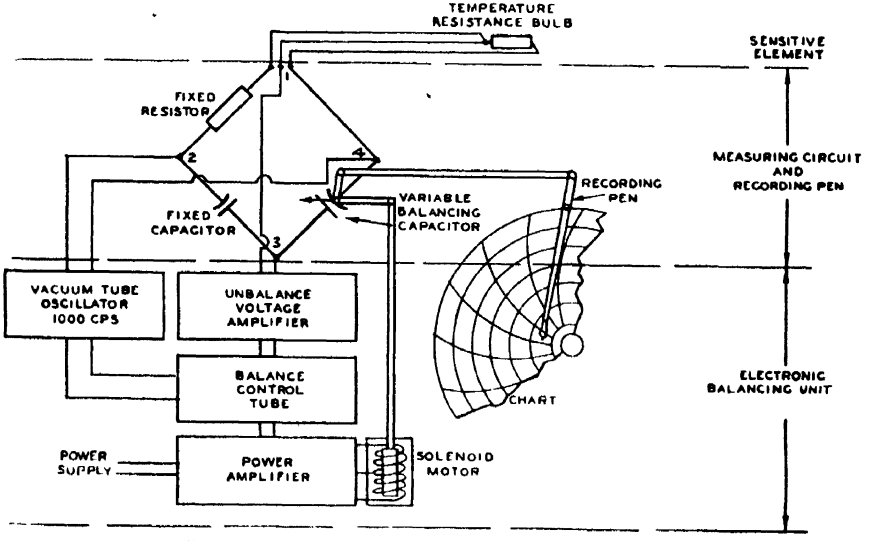


FIG. 83 —Controller system (Foxboro Co.).

slide wire so as to restore the balance and the temperature may be indicated on a scale at the slide wire or similarly recorded by the inked pen on the circular chart. With a controller in operation the motor also operates the controller mechanism for the heat supply.

The arrangement represented in Fig. 83 is the basis of the system used by The Foxboro Co. of Massachusetts, U.S.A., and the associated company Foxboro-Yoxall Ltd., of London. The main features of this arrangement are that it dispenses with galvanometers, batteries and slide wire resistances. The resistance thermometer is inserted in one arm of a Wheatstone bridge circuit, while the fixed resistor, the fixed condenser or capacitor, the variable condenser or balancing capacitor are in the other three arms as shown. The moving part of the balancing capacitor is connected to the recording pen and to two solenoids. An alternating potential of 1000 cycles per second is induced across the corners 2, 4, of the bridge and is due to an oscillating valve circuit of standard design, that is, a suitable proportion of the anode output is fed back to the input or grid in the correct phase. If the bridge is in balance an equal and opposite current is fed to these two solenoid coils, and the cores are thus held in balance by equal and opposite forces. A change in the resistance of the thermometer coil due to a change of temperature upsets the balance of the bridge, and the resulting changes of voltage between the other points of the bridge are fed to the voltage amplifier to be magnified by 20,000 to 100,000 times. This amplified out-of-balance is passed into the balance control where a thermionic valve detects the way the circuit is unbalanced, and through the power amplifier causes an increased current to flow through one of the solenoid coils and a decreased current through the other. This effect provides the turning forces to move the condenser or balancing capacitor and the recording pen until a new balance is obtained. The control device of the controller, when installed, is also operated from this mechanism.

The condensers, resistances and other circuit elements are placed in separate enclosures or containers which are then evacuated, filled with oil, and hermetically sealed to protect these elements against the effects of high ambient temperatures,

humidity, corrosive fumes, and the like. The resistance thermometer coil may be given different mountings according to the use. For instance, to measure, record or control the temperature of steam-heated rolls in the manufacture of paper, plastics, rubber and textile goods and similar operations, the coil is mounted on a block of marinite for support and is carried by a floating spring-suspended face plate made of graphited bearing material curved to the same curvature as the roll against which it lightly presses with negligible friction. In this case the controller would automatically open or close the steam supply valve to the rolls as may be required.

The same principles are adopted with thermocouples for measuring, recording or controlling temperatures. The thermocouple is a part of the potential meter circuit where the thermocouple potential is compared directly with that derived from a standard cell, thus eliminating the use of a dry cell or battery and of the comparison of this with the standard cell. This direct use of the standard cell is practicable where the thermionic valves operate without requiring appreciable anode current. In this arrangement the actual peak current drawn from the standard cell may be about 1×10^{-7} amp., and is nearly equivalent to connecting the standard cell across an impedance of 1×10^{7} ohms. This high impedance circuit makes it possible to insert as much as 5000 ohms in the thermocouple leads without affecting appreciably the sensitivity, speed or accuracy of the instrument.

The balancing and controlling systems which have been described may be used in any measuring or controlling process where the physical properties under control, such as pressure, strain, density, conductivity, humidity, pH, etc., can be translated into electrical resistance, potential or current, etc. Reference may be made to *The Instrument Manual* (United Trade Press, Ltd.), for details of instruments designed for these purposes, and to *Instrumentation* (Honeywell-Brown Ltd.).

Reference has been made to the automatic control of oil-, gas- or coal-fired furnaces. Many arrangements are available for small and for large furnaces, with natural draught or with forced draught conditions of operation, and it is hardly possible in the space available to describe or to discuss all the types of burner or stoker installations. As an example of a compact

firing unit Fig. 84 illustrates a fully automatic heavy oil burner plant suitable for supplying about 8,000,000 B.Th.U. per hour to the furnaces of all types of steam and hot-water boilers. It is built by the Clyde Fuel Systems Ltd., of Glasgow, and comprises a fan with air regulator direct driven by electric motor, oil fuel pump driven through a flexible coupling from the end of the motor shaft, continuous automatic cleaning suction and discharge oil strainers, oil burner with diaphragm,

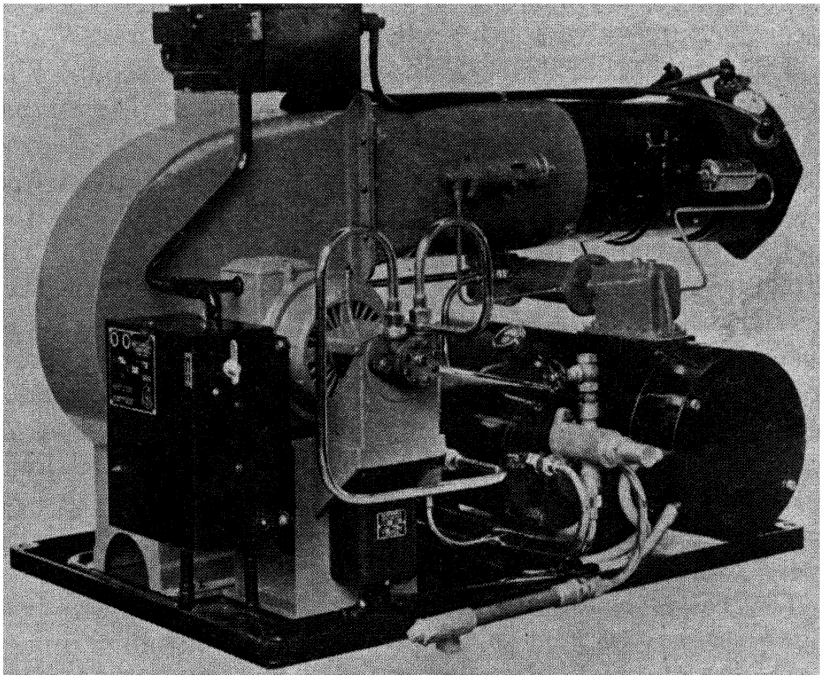


FIG 84.—Automatic oil burner system with forced draught (Clyde Fuel Systems Ltd).

nozzle and automatic shut-off valve, blast pipe with air director, oil-operated oil shut-off valve to seal the blast pipe when the plant is at rest, ignition transformer and electrodes to ignite the atomised oil, thermostatically controlled oil heater for hot-water or steam boilers, and automatic control panel to time the sequence of operations. The controls include a flue thermostat to close down the plant in the event of flame failure, an immersion thermostat for hot-water boilers to maintain a predetermined water temperature at the outlet, or a pressure

switch for steam boilers, and room thermostats to maintain predetermined room temperatures.

The same firm build compact underfeed coal stoker units with motor-driven forced draught fans, with or without thermostatic or pressure switch control. For hot-water boilers two temperature controlling thermostats are supplied, one for ordinary control and another set to a limit about 10° F. higher so that it will close down the stoker should the ordinary thermostat become deranged. In cases where the stoker may be out of action for rather long periods of time, as may occur with on-off or two-step control, a kindling switch can be incorporated which brings the stoker into action for short periods at any predetermined time, thus preventing the fire from becoming extinct.

Many examples could be given of the economies to be derived in industry through the automatic control of temperatures, but one case may suffice at present. It refers to the new normalising furnaces at the works of the * Taylor-Wharton Iron and Steel Co., Easton, Pa., in the production of high-pressure steel gas cylinders. Instead of heating these cylinders in batches to 1700° F. the oil-fired furnaces were reconstructed with three zones kept at suitable temperatures by automatic controllers operating through the temperature signals from radiation pyrometers. The cylinders now pass through each zone in series and leave the last zone at 1450° F. (only 40° F. above the critical temperature of 1410° F. for this steel). The labour force required was thereby reduced to about one-sixth, the time of heating was reduced to less than one-quarter with more uniform quality in the products. In addition, the work is heated so rapidly that practically no scale is formed on the steel surface, which greatly reduces the time required subsequently for cleaning operations. The fuel or heat consumption has been reduced from $5\frac{1}{2}$ to 1·15 millions B.Th.U. per ton of steel.

* *Instrumentation*, No: 5. 1950.

CHAPTER VI

VARIOUS OTHER PYROMETERS

Calorimetric Pyrometers.—This method was one of the earliest in use for the estimation of high temperatures. A suitable small piece of metal is subjected to the temperature it is desired to measure and when uniformly heated is rapidly transferred into a vessel of water well insulated to prevent loss of heat externally. From the known weight and specific heat of the metal and the known weight of water and the water equivalent of the apparatus, together with the rise of temperature of the water, a simple calculation gives an estimate of the initial temperature of the piece of metal.

Thus, if m = weight of metal heated.
s = mean specific heat of metal.
T = temperature of metal before immersion.
t_1 = initial temperature of water in calorimeter.
t_2 = final " " " " "
W = weight of water in calorimeter.
w = water equivalent of calorimeter.

Then Heat lost by metal = Heat gained by water.

Or, $$ms(T-t_2)=(W+w)(t_2-t_1).$$

Or, $$T=\frac{(W+w)(t_2-t_1)}{ms}+t_2.$$

In practice it is necessary to take precautions to ensure a reasonable degree of accuracy by this method. One difficulty is to obtain a metal which does not oxidise at high temperatures. Platinum is too dear for the purpose. Iron and copper oxidise on immersion and the oxidised surface peels off. Nickel has been found to be fairly suitable if not heated beyond 1000° C. (1832° F.) Another difficulty is the specific heat of the metal, which usually varies with the temperature, and an exact determination is hardly ever obtainable. Also there is nearly always a loss of heat and an unknown fall of

temperature of the heated metal during its transfer to the calorimeter. Notwithstanding the liability of such instruments to considerable errors when used carelessly, they are of some service for an approximate estimate of temperatures, say to within 20° or 30° F. at 1500° F., when only an occasional determination is required, or where the importance of the measurements would not justify the installation of the more elaborate and perhaps more expensive pyrometers previously described.

The following values may be taken to represent the total heat in one pound of nickel measured from 0° C. (32° F.).

HEAT IN 1 LB NICKEL FROM 0° C OR 32° F.

Temperature		B Th U per pound.
° C.	° F.	
0	32	0
100	212	20·7
200	392	41·9
300	572	71·1
400	752	91·8
500	932	116
600	1112	138
700	1292	164
800	1472	189
900	1652	216
1000	1832	245

An industrial form of the calorimetric pyrometer, is illustrated by the sectional view in Fig. 85. It consists of a double copper cylinder, the inner portion containing water and insulated from the outer with felt to prevent the external loss of heat. This double cylinder is enclosed in an outer copper cylinder *a* with an air space. The thermometer at *b* is protected from damage by a perforated brass tube, and near the stem of the thermometer is placed a sliding piece *c* carrying a pointer, and on *c* a temperature scale is marked. In using the instrument the specified quantity of water is placed in the calorimeter and the pointer on *c* is brought opposite the top of the mercury column in the thermometer. The metal cylinder is heated in the crucible or special muffle until it is

certain to have acquired the proper temperature to be measured and is then rapidly withdrawn and dropped into the water. After shaking the instrument to ensure a uniform temperature in the water the column of mercury is watched, and on attaining its highest position the reading given on the scale *c*, added to the initial reading of the thermometer, denotes the temperature of the hot metal. If the instrument has been calibrated against the more accurate platinum resistance or the thermo-electric pyrometers under definite conditions of manipulation a fair degree of accuracy is attainable.

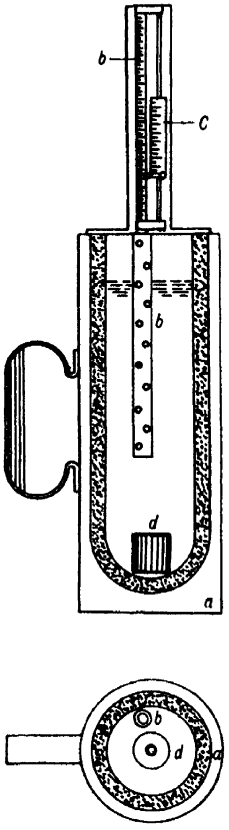


FIG. 85.—Siemens' calorimetric pyrometer.

Messrs. Siemens Bros. and Co., Ltd., suggested the following metals as suitable within the specified ranges:

For temperatures up to:

1800° F. or 1000° C.—Copper or iron.

2200° F. or 1200° C.—Nickel.

2700° F. or 1500° C.—Platinum.

The original weights of these metal cylinders supplied with the instrument are: copper, 137 grms.; wrought iron, 112 grms.; nickel, 117 grms.

As mentioned previously, in course of time the copper and iron cylinders lose weight by scaling. The makers can supply tables of factors for these metals by which the readings on the sliding scale *c* are multiplied according to the actual weight of the cylinder.

Expansion and Contraction Pyrometers.—About 1782, Wedgwood, the famous potter, introduced his contraction pyrometer for the arbitrary estimation of the temperatures in his kilns or furnaces. His method consisted in the measurement of the contraction of small cylinders made from special clay after having been subjected to the temperature. His measuring device was a tapered groove, and each inch of length was divided into twenty equal parts, making 240 divisions altogether; each division was called one degree. The width

of the groove at the zero mark was 0·5 in. and at the 240 mark was 0·3 in.

In recent years the Wedgwood pyrometer has been improved both in the materials and in the form of the test-piece. In 1900 Watkin introduced discs of clay with a hole in the centre so as to facilitate withdrawal from the furnace or kiln. The diameter of the disc is measured to a thousandth of an inch in a manner similar to that of Wedgwood.

Buller's trial rings of clay are of similar form and measure 2½ in. in diameter. The contraction of the ring during the different stages of firing is measured on a special gauge.

The Joly "Meldometer" has been used to determine melting-point temperatures of metals and salts. It consists of a thin platinum strip supported under a slight tension between two points on levers, and the strip can be heated by an electric current. The change of length of the platinum strip with changes of temperature is measured by micrometer screws. A previous calibration gives an estimate of the temperature of the strip from the measured change of length. In determining the melting point of a metal or of a salt a speck of the specimen is placed in the middle of the strip under the view of a low-power microscope. The current is increased gradually, and at the instant of melting, as observed through the microscope, the micrometer is set and read. This instrument is not of much service for industrial work.

A practical pyrometer making use of the relative expansion of a bimetallic strip was described on p. 32.

Fusion Pyrometers.—When the fusing or melting point of a metal, alloy or salt is known, use may be made of this to indicate approximately the attainment of particular temperatures in a furnace. By selecting a number of solids with suitable melting or fusing points and inserting these in the furnace in a suitable manner a rough estimate of the furnace temperature may be obtained, since the temperature may be taken to be equal to or higher than the point of fusion of a substance which fuses in the furnace and lower than that of a substance maintaining its original shape at that temperature.

Messrs. Vogt and Light, of Paris, were the first to use cones made of suitable mixtures of china clay, felspar, lime, etc., with progressive fusing temperatures. Seger, in 1886, after

experiments made at the Royal Pottery Works in Berlin, published the results of his investigations on the use of silicates of progressive melting points for the estimation of furnace temperatures. The shape of the "cones" is that of triangular pyramids of 15 mm. side and 50 mm. high. When softening begins under the action of heat the tip of the pyramid manifests an alteration of form and finally the pyramid bends over completely.

The Seger cones are now manufactured in this country and are obtainable from several firms such as Messrs. Keeling & Walker, Ltd., and Messrs. Wengers, Ltd., both of Stoke-on-Trent. The cones are used extensively in the pottery and clay industries in standardising the firing of ovens and kilns. Different melting or fusion points are provided by varying the composition of the cones and each cone has a distinguishing number. About one-half of the numbers are reproduced in the table given below. The squatting temperatures in this table were determined by heating the cones for two hours at the specified temperatures. If the cones are "soaked" for a long time they squat at lower temperatures; for instance, if cone number 10 is soaked for three days its squatting temperature is reduced to about 1180° C. In actual firing of kilns time is nearly as important as temperature, and a prolonged soaking fire at a relatively low temperature may do the same "work" in maturing a body or glaze as a quicker firing at a higher temperature. Accordingly, during the firing of an oven or kiln, the "work" done on the body or the glaze and on the cones will be nearly proportional to one another.

The original numbers of the Seger cones started at number 1. Since then the lower fusion temperatures have been added with numbers downwards from one by affixing the cypher. In practice three or four of the cones are selected having melting points known to be near to the temperatures required, and are inserted into the oven or kiln on a slab of refractory material at as many places as may be necessary, but without allowing the direct impingement of flames on the cones. When the lowest number of cone begins to bend, as seen through a sight hole, it is a signal to the fireman that the firing period is approaching completion. If the cones have been properly

selected the highest numbered cone would still be erect at the end of the firing period.

EXAMPLES OF APPROXIMATE SQUATTING TEMPERATURES OF STAFFORDSHIRE SEGER CONES AFTER HEATING FOR TWO HOURS

Cone No	°C.	°F.	Cone No	°C	°F	Cone No	°C	°F	Cone No	°C	°F
022	600	1112	06	980	1796	10	1300	2372	30	1670	3038
020	670	1238	04	1020	1868	12	1350	2462	32	1710	3110
018	710	1310	02	1060	1940	14	1410	2570	34	1750	3182
016	750	1382	1	1100	2012	16	1460	2660	36	1790	3254
014	815	1499	3	1140	2084	18	1500	2732	38	1850	3362
012	855	1571	5	1180	2156	20	1530	2786	40	1920	3488
010	900	1652	7	1230	2246	26	1580	2876	42	2000	3632
08	940	1724	8	1250	2282	28	1630	2966			

Various modifications of the cones have been introduced, such as Wengers " Calorites " and Watkin " Heat Recorders." In America what are called Orton cones are widely used. Messrs. Holdcroft and Co., of Stoke-on-Trent, produce " Thermoscope " bars supported at their two ends on a refractory base. Usually a series of four of these bars having progressive fusion points are accommodated. The condition is easily recognised by the sagging of a bar at the fusion point.

The fusion points of metal alloys of definite composition have been used by various experimenters for the estimation of furnace temperatures. They have also been used to indicate the temperature of boiler plates and tubes by embedding plugs of the fusible alloys in the metal of the plates. This method, however, when compared with the more modern methods available for measuring plate temperatures, is now considered to be unreliable.

Temperature-Indicating Paints or Colours.—The measurement of the surface temperatures attained by moving machine parts or by articles during manufacture is often desirable, but in some cases is rendered difficult owing to the rapid motion or inaccessibility of the part or article. Temperature-indicating paints or colours have been developed * which are capable by their changes of colour of giving an overall picture of the distribution of temperature on a heated

* " Temperature-Indicating Paints," by L. C. Tyte, *Proc. Inst. Mech. Engs.*, 1945, Vol. 152, No. 2, p. 226.

surface, and have been used to measure the temperatures attained by cutting tools, by the internal and external surfaces of engine parts, the uniformity of the heat treatment of large objects, or as a check on the suitable heat treatment of particular items, and the like. It should be understood, however, that this method is not intended to replace the more orthodox methods of measuring temperatures where accurate results are required, but it may be valuable for use under actual production conditions or in research, if used with care.

A range of "Thermetric" colours have been produced by the Imperial Chemical Industries, Ltd., consisting of a series of pigments in liquid form, and may be readily applied to the surface of the object. Visual examination at the end of a prescribed period of heating indicates the temperature attained by the object. Broadly speaking, these colours consist of a heat-sensitive pigment incorporated in a synthetic resin dissolved in a volatile solvent, the resin having been selected specially on account of its stability towards heat and resistance to attack by oil. The pigments themselves vary widely in composition from wholly inorganic materials to those containing a high proportion of organic matter combined with metallic derivatives, and mostly owe their change of colour to the loss of water, carbon dioxide, ammonia or other volatile constituents at the temperature specified. On this account the temperature of the colour change will vary to some extent with the duration of heating and colour changes may be obtained by prolonged heating at temperatures well below those given for 30- or 60-minute heating periods. The reversible colours all operate by dehydration followed by rehydration on cooling in a normal atmosphere, and will not act reversibly if insufficient moisture is present for the latter process. Similarly, such colours will not function if completely covered by a layer of varnish through which water vapour cannot diffuse readily.

In order to use these colours, it is only necessary to select colours corresponding to the desired or expected temperatures, stir them thoroughly and apply thin films to the object with a brush or a spray gun. The surface of the object should be free from oil or dirt before the application. The colours dry very rapidly.

Many of these "Thermetric" colours are now available in three groups.

1. Single-change colours (non-reversible on cooling).
2. Double-change colours (second change only non-reversible).
3. Multi-change colours.

The following is a short selection of the available colours.

	Thermetric colour.	Temperature of change, ° C. Heated for		Colour change.
		30 mins.	60 mins.	
Group 1	P	80	80	Grey blue to olive green
do.	H	420	400	Purple to white
Group 2	C	55	50	Pale pink to green, reversible
		220	210	,, ,, to black
Group 3	MB	210	210	Pale green to dark straw
		230	230	,, ,, to black
		300	300	White to fawn
do.	HB	400	390	,, to beige
		700	700	,, to white

CHAPTER VII

THE MEAN TEMPERATURE OF A METAL WALL

THE best arrangement for measuring the mean temperature of a metal wall depends somewhat upon the thickness and general accessibility of the wall and upon the degree of accuracy required. While it is generally convenient, for example, to find the mean temperature of a steam engine or a gas engine cylinder by means of mercury thermometers placed in drilled holes in the metal, such an arrangement would hardly be possible for an engine piston or for the thin wall of a condenser tube.

It is well known that there are practically no cyclical changes of temperature in the wall of a steam engine or an internal combustion engine cylinder at a depth of $\frac{3}{8}$ in. or so from the working surface under ordinary conditions of operation. Therefore it follows that a small-diameter mercury thermometer placed in a drilled hole in the metal at this distance from the surface would give the mean temperature at such a point, provided the hole was only slightly larger than the thermometer, and that a little mercury was inserted to increase the thermal contact between the thermometer and the metal and to reduce the tendency of the hole to disturb the flow of heat through the metal. An approximate estimate may sometimes be obtained by binding a thermometer with its bulb in contact with the cylinder wall and then surrounding the bulb with non-conducting material on the outside. This method, however, is somewhat crude and is liable to large and uncertain errors.

The late Mr. Bryan Donkin appears to have been the first experimenter to use mercury thermometers in drilled holes for the measurement of cylinder wall temperatures.* Some of his experiments were conducted on a small steam engine ;

* *Proc. Inst Civil Engs.*, Vol. C, 1889–90, Part II ; *ibid.*, Vol. CVI, 1890–91, Part IV ; *ibid.*, Vol. CXV, 1893–94, Part I , *Proc. Inst. Mech. Engs.*, 1893, p. 480 , *ibid.*, 1895, p. 90 ; *ibid.*, 1896 ; *ibid.*, 1900, p. 509.

others on small thick cylinders of various materials but without piston, a small piston valve being operated by an engine so as to admit, cut off, and liberate steam from the experimental cylinder. Others again were made on short thick cylinders of various materials having water flowing through the central hole and steam outside the cylinder.

In some experiments made by Professor A. L. Mellanby *

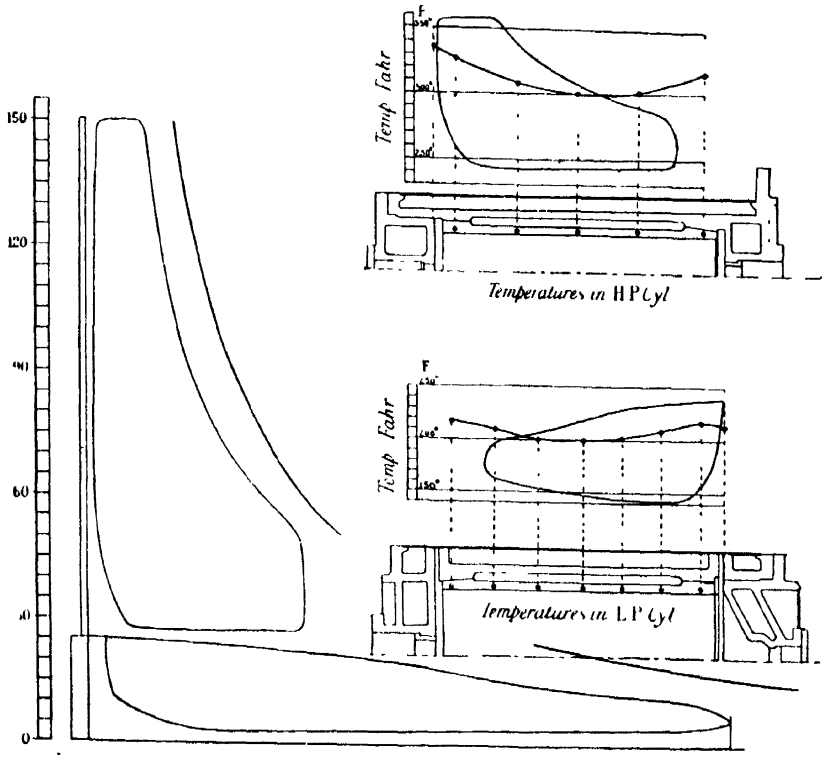


FIG. 86—Pressures and mean temperatures in steam engine cylinders (no steam in jackets).

on a horizontal compound side-by-side steam engine, with high pressure cylinder 11½ in. diameter, low pressure cylinder 20 in. diameter and stroke 36 in., mercury thermometers were inserted at various points along the length of the cylinder liners as represented in Figs. 86 and 87. Here also is shown the mean

* "An Investigation to Determine the Effects of Steam-Jacketing upon the Efficiency of a Horizontal Compound Steam-Engine," *Proc. Inst. Mech. Engs.*, June, 1905.

temperatures in the metal compared with the saturation temperatures of the steam in the cylinder as determined from the pressures on the indicator diagrams. Fig. 86 illustrates the conditions without steam in the jackets, while Fig. 87 shows the effect of steam in all the jackets. In both cases the engine was running at about 60 revolutions per minute with the nominal total number of expansions 12·3.

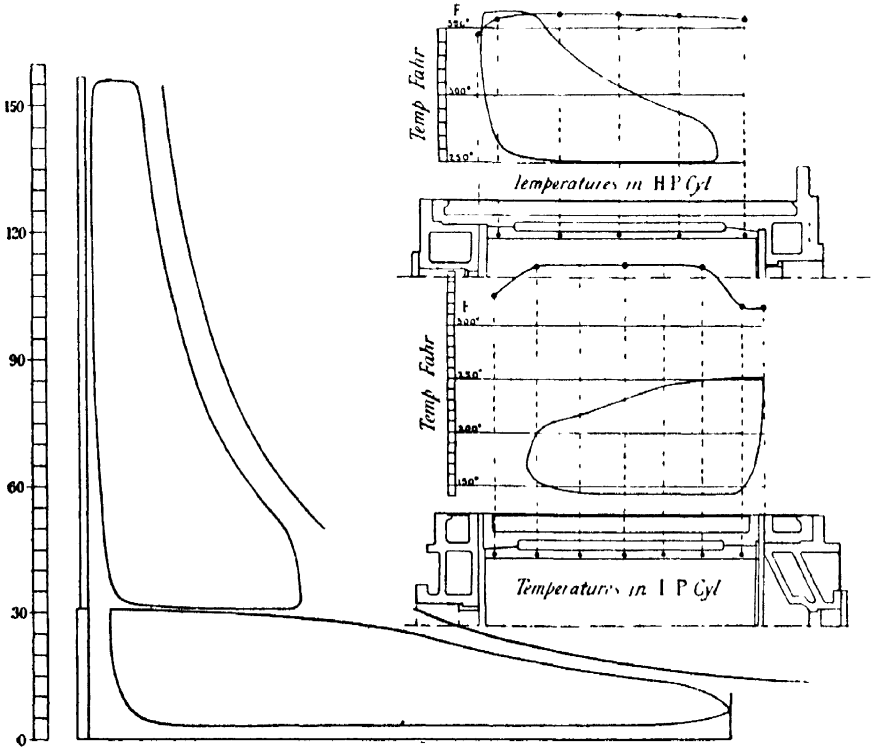


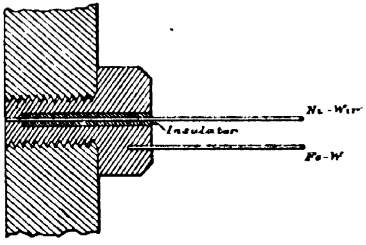
FIG. 87.—Pressures and temperatures in steam engine cylinders (steam in all jackets).

Professor Callendar * used iron and nickel thermojunctions to measure the mean temperatures at various points of the thin cylinder wall of a small air-cooled petrol engine. The wires of iron and nickel were about one millimetre in diameter and each pair forming a couple were firmly screwed, side by side, into small holes in the cylinder (cast iron) so as to get good electrical and thermal contact. This is equivalent to con-

* "Some Experiments on an Air-Cooled Petrol Motor," *Technics*, April, 1904.

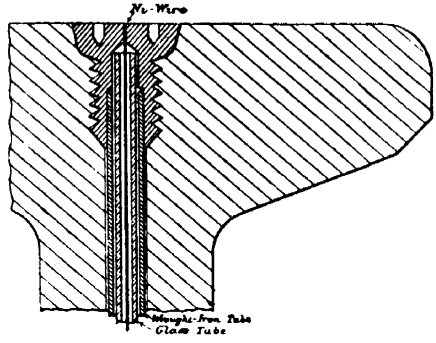
necting the nickel and iron wires together to form the couple, provided the connecting material, in this case cast iron, is homogeneous and at the same temperature as the connected ends of the wires. Eight couples were employed in different positions and any couple could be connected to a millivoltmeter. One of the couples was calibrated against a standard platinum resistance thermometer, and it was found that the thermo-electric power $\frac{de}{dt}$, of the couple fell to less than half its initial value between 300° C. and 400° C., but increased again at higher temperatures.

The late Professor Hopkinson * used the wrought-iron



SECTION OF THERMO-COUPLE USED IN PISTON

FIG. 88.



SECTION OF THERMO-COUPLE USED IN EXHAUST-VALVE

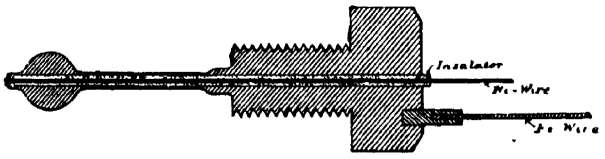
FIG. 89.

nickel thermocouple to measure the mean temperatures at particular points of the uncooled piston, exhaust valve, and inlet valve of a Crossley gas engine working on the four-stroke cycle. The cylinder diameter was 11½ in., the stroke 21 in., and the engine was designed to give a maximum of 40 b.h.p. at 180 revolutions per minute. The compression pressure was about 160 lb. per sq. in. above atmospheric pressure. The ignition was by magneto and the governing by hit and miss. Cambridge coal gas was used as the fuel throughout these experiments.

The arrangement of the thermocouples is shown in Figs. 88, 89 and 90. Fig. 88 shows the construction of one of the piston thermocouples, of which three were used, one at the

* "Heat Flow and Temperature Distribution in the Gas Engine," *Proc. Inst. Civil Engs.*, Vol. CLXXVI, 1908–09.

centre and the other two at different radii from the centre. The one used in the exhaust valve is illustrated to full size in Fig. 89, and a similar thermocouple was used in the inlet valve. The thermocouple shown in Fig. 90 was arranged to project into the centre of the combustion chamber in order to study the temperatures at which such a projection would cause pre-ignitions. Each thermocouple consisted of a nickel wire brazed into the wrought-iron bolt. The nickel wire was passed through a hole drilled along the axis of the bolt from which it was insulated by means of a glass tube set in plaster of Paris; it was then brought through a small hole at the end of the bolt, $\frac{3}{16}$ in. deep where it was brazed to the iron, and the end of the wire was cut off flush with the end or the head of the bolt. A wrought-iron wire was brazed into the bolt, and to complete the circuit copper leads were sweated



SECTION OF BOLT USED FOR OBTAINING PRE-IGNITIONS

FIG. 90.

to the nickel and iron wires respectively at a distance of 3 ft. or so from the bolt, connecting the thermocouple through an adjustable resistance to a reflecting galvanometer.

The nickel wire was obtained from Messrs. Johnson, Matthey and Co.; it was 0·015 in. diameter, and the same batch of wire was used for all the thermojunctions. The bolts were of ordinary wrought-iron, and common wrought-iron wire was used. There was no material thermo-electric force between the iron wire and the bolt. The thermocouples were calibrated in an electric furnace against a Callendar platinum resistance thermometer and one such calibration curve is shown in Fig. 91, with the cold junction (i.e. the connections of the copper leads to the iron and nickel wires) at 0° C. The same leads, resistances and galvanometers were used in the calibration as in the engine, the bolt containing the couple being simply transferred from its place in the engine to the furnace. It was thus possible to use a low resistance galvanometer; about 5·8 ohms for galvanometer and leads, making 21·8 ohms for

the whole circuit. One division on the galvanometer scale was equal to 2·57 microamperes, or 56 microvolts. The thermocouple registered, with sufficient accuracy for the purpose, the excess of its temperature over that of the junctions between the iron and nickel wires and the copper leads.

In regard to piston temperatures, the actual temperature at the centre of the piston, with the jacket outlet temperature at 70° C. (158° F.), was about 370° C. (698° F.) when the total heat loss to the jacket water was about 1600 B.Th.U. per

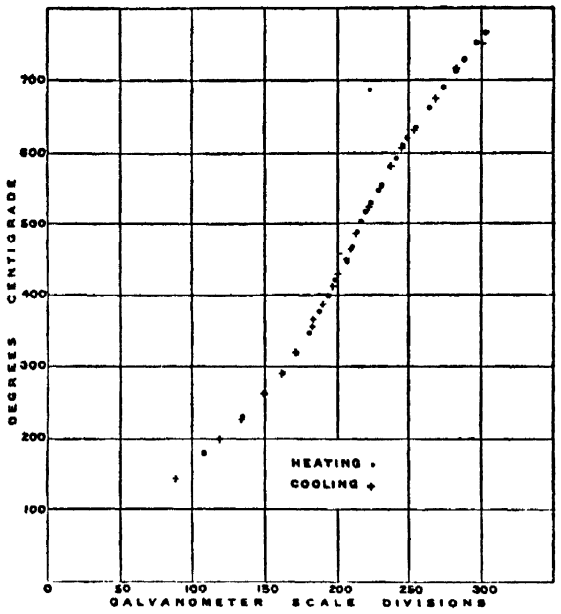


FIG. 91.—Calibration curve for wrought-iron, nickel thermocouple.

minute, and it was estimated that under these conditions the temperature at the edge was about 182° C. below that at the centre. The highest recorded temperature at the centre of the piston was 480° C. (896° F.).

Under ordinary running conditions with a medium gas-charge and with a loss of about 1600 B.Th.U. per minute to the jacket, the temperature at the centre of the exhaust valve was about 400° C. (752° F.), and at the centre of the inlet valve about 250° C. (482° F.). With heavy charges the exhaust valve reached 500° C. (932° F.). The thermocouples showed small cyclical fluctuations of temperature, and theoretically

would represent those occurring where the nickel wire left the wrought iron bolt at the depth of $\frac{3}{16}$ of an inch, provided the thermo-electric contact there was good.

When the thermocouple shown in Fig. 90 was inserted it was found that if the gas mixture was rich enough to raise the temperature of the end to a little above 700° C. (1292° F.) persistent pre-ignition would be caused and the engine would be rapidly pulled up. It was also found that when the end of the bolt reached about 800° C. (1472° F.) back-firing was caused, that is, the charge ignited as soon as it entered the engine. An arrangement was also fitted vertically over the exhaust valve by means of which oil could be dropped on to the centre of the valve, and it was found that in this way pre-ignitions of considerable violence could be produced when the exhaust valve had a temperature as low as 450° C. (842° F.), but these pre-ignitions only persisted as long as the oil was allowed to drop on the hot surface.

A large number of tests were also made with different strengths of the gas mixture, and within fairly wide limits it was found that the temperature of pre-ignition was independent of the strength of the mixture. Injection of water into the engine through the suction-valve provided for that purpose reduced the rate of rise of temperature of the bolt and sometimes prevented it from reaching the critical temperature. Even in considerable quantities, however, the water did not alter the temperature at which pre-ignition occurred, although it had a tendency to prevent the critical temperature of pre-ignition from being attained.

Although it is convenient for calibration purposes to have the thermocouple constructed as in Professor Hopkinson's tests, it is evident that the insertion of the wrought-iron plug in the cast iron involves a screwed joint which may not be in the same condition as the normal body of the cast iron, and the plug may attain a temperature several degrees higher than the cast iron. There is also the possibility of parasitic or localised currents being set up by the contact of the wrought-iron plug and the cast iron, though it must be said that it is hardly likely this would affect the thermocouple at the centre of the plug.

As mentioned on p. 61, base metal thermocouples are liable

to alterations of thermo-electric force in course of time with prolonged usage. For experiments of comparatively short duration there is probably not much difficulty—Professor Hopkinson said that he had no difficulties with his thermo-couples due to prolonged exposure—but Colonel Crompton, in discussing Professor Hopkinson's paper,* reported that he himself had not succeeded in getting satisfactory results with iron-nickel thermocouples, instancing a case where such a couple underwent a decrease of 10% to 15% in e.m.f. in the course of six months after the couple was first put together, with exposure to temperatures of about 700° C. (1292° F.).

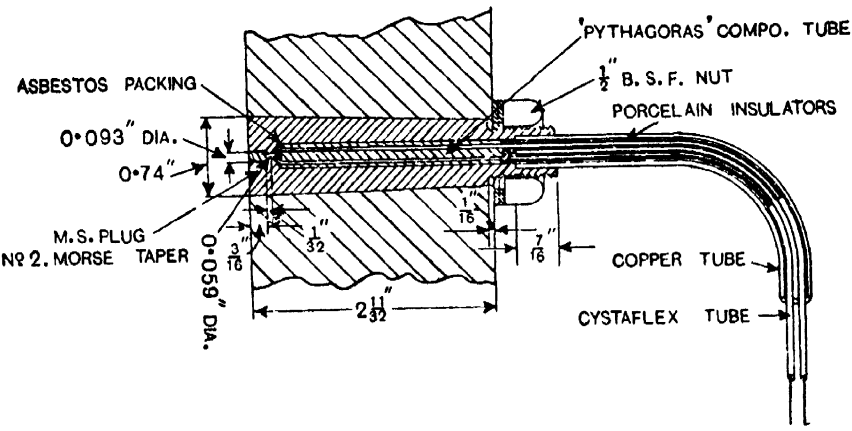


FIG 92.—Piston thermocouple

It is not possible to describe here in detail all the modifications in thermocouple designs which have been adopted in recent years to measure or estimate the mean temperatures of cylinder liners or piston walls, and a selection of the more important or progressive arrangements is therefore necessary. Tests were made by Prof. G. F. Mucklow, D.Sc.† on a Crossley solid-injection horizontal single-cylinder oil engine working on the four-stroke cycle. The cylinder diameter was 14 in. and the stroke 23 in., with the full load rating of 66 b.h.p. at 212 r.p.m. Two types of thermocouples were employed, the first type being designed to measure temperatures close to the outer surface of the piston wall and shown in Fig. 92, while

* *Proc. Inst. Civil Engs.*, Vol. CLXXVI, 1908–09, Part II, p. 46.

† " Piston Temperatures in a Solid-Injection Oil Engine," *Proc. Inst. Mech. Engs.*, 1932, Vol. 123, p. 349.

the second, represented in Fig. 93, was arranged to give the temperature of the inner surface. Silver-constantan couples were chosen in the expectation that these would give relatively high e.m.f.s up to about 600° C., but trouble was experienced with these couples in the neighbourhood of the end projection or knob on the piston, and for these positions the couples were replaced by similar units having nickel and nickel-chrome wires brazed in the MS plugs.

The hot junctions shown in Fig. 92 were made by twisting

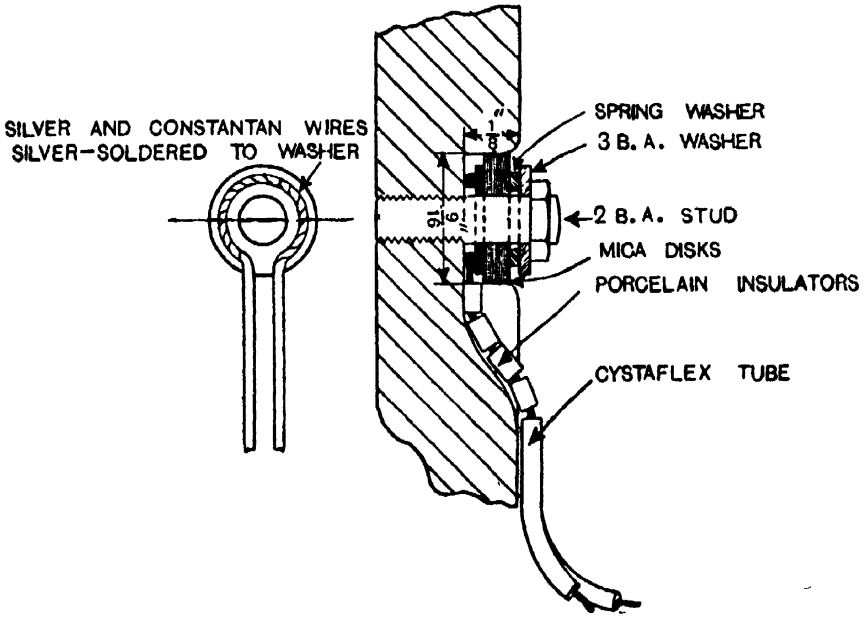


FIG 93 —Piston thermocouple.

together the No. 22 I.W.G. wires and silver soldering or brazing the junction so formed into a hole $\frac{3}{16}$ in. deep in the head of the tapered steel plug. The hot junctions represented in Fig. 93 were of silver-constantan wires twisted together and silver soldered to one side of a brass washer, bolted into contact against the wall with mica washer insulation under the nut. A flexible stranded copper wire was soldered to each thermocouple wire and then carried along a linkage, and finally soldered to the corresponding wire of the cold junction. The cold junctions were insulated and placed in a thermos-flask with ice. Mercury contact switches connected each thermocouple to the galvanometer.

In the calibrations two or more thermocouple plugs to be calibrated were placed in a fireclay crucible, packed with iron filings, and a layer of asbestos wool was placed over the surface. This crucible was next immersed in molten tin contained in a fireclay vessel and heated by a Bunsen burner. A standardised high-reading mercury thermometer was used for comparison up to 550° C. (1022° F.) and above this a standardised rare metal thermocouple was used instead.

The highest temperatures were recorded at the centre of the piston projection or knob ranging from 353° C. (668° F.) at no load to 650° C. (1202° F.) at full load. The temperature at the outer edge of the knob was about 570° C. (1058° F.), and at the root about 550° C. (1022° F.), at full load. These temperatures are certainly high for ordinary cast iron under load and this feature has no doubt been partly responsible for the general avoidance of such projections on pistons of modern design.

Further experiments to be considered were made by Prof. H. Wright Baker, D.Sc.,* on a standard vertical Mirrlees Diesel oil engine having a cylinder diameter of 12 in., with the stroke 18¼ in., and normal speed 250 r.p.m. Two cast-iron pistons and one aluminium piston were tested. The wires used for the thermo elements in the cast-iron pistons were of iron and "Eureka" (constantan) of 22 I.W.G. and of copper-"Eureka" of 24 I.W.G. for the aluminium piston. The wires for the aluminium piston head were brazed together to form a small bead and two short lengths of porcelain pushed on the wires up to the junction, the remainder of the wires being heavily insulated with double silk winding and a casing of cotton impregnated with shellac. A hole ½ in. deep was drilled in the outside face of the piston and then tapped ½ in. B.S.F. thread. Two small holes were drilled at an angle from the base of the hole to the inside of the piston. The wires and porcelain insulation were passed inwards through the two small holes to the inside of the piston. The junction bead was pressed on to the metal at the bottom of the ½ in. hole by means of a screwed aluminium plug with a keyed brass washer intervening

* "The Operating Temperatures of Cast Iron and Aluminium Pistons in a 12-inch Bore Oil Engine," *Proc. Inst. Mech. Engs.*, 1934, Vol. 127, p. 217.

to prevent twisting of the thermocouple as the plug was screwed home. In the cast-iron pistons the thermojunction bead was pressed into the bottom of the hole, bored from inside the piston, by a clamp acting on a twin-bore porcelain tube. A similar arrangement was used to determine the temperatures of the cylinder liner after screwing a sleeve through the water jacket to make watertight joints at the liner and at the jacket wall. Temperatures inside the pistons were obtained by the " washer " type of junction similar to that shown in Fig. 93, p. 192. A few rib temperatures for the cast-iron pistons were measured by clamping the bead against the rib with mica and asbestos washer insulation.

The insulated leads inside the pistons were protected by tubes of " Cystaflex " and were clamped securely in position on one side of the base of the skirt. The vertical A frame of the engine did not allow of linkwork to carry the leads as in the horizontal engine previously considered. Instead of this for a short distance after leaving the piston the heavily insulated leads were laced together to form a flat belt and were attached tangentially to a semicircular drum about 14 in. diameter mounted underneath on an axis at right angles to the engine crank-shaft. The leads were then carried for about 6 ft. along a framework of steel blades moving with the drum at that end but attached to a stationary hinged frame at the other end and thence to a common cold junction at 0° C. and to the Unipivot millivoltmeter through double-pole mercury contact switches. The drum was oscillated through nearly 180° by a Bowden cable operating over guide pulleys from a crank and connecting rod on the end of the crank-shaft acting in proper unison with the engine piston so as to keep the leads from the piston to the drum under a slight tension.

An attempt was first made to use continuous wires but it was soon found that the copper leads fractured after a short period of running at the point where they were bent at the drum. For the couples employing copper, therefore, lengths of flexible copper wire were inserted into all leads where these were subjected to bending, while Bowden cable was similarly inserted in couples using iron. Owing to the introduction of thermo-elements thus formed by the Bowden cable inserts, a

compensating Bowden-constantan couple was used throughout the tests with the cast-iron pistons.

The lengths of flexible copper wire inserted in the leads at the danger points constituted subsidiary thermojunctions. No important errors were introduced by these junctions or couples at the clamp to the drum as they were at room temperature, but errors due to these connections at the piston had to be taken into account because of a gradient of temperature there. The continuous conductors lasted long enough to make it clear that the flexible copper leads made the piston temperatures consistently 3° C. too low and this correction to the readings was made. In the case of the cast-iron pistons, where flexible wires of Bowden cable were inserted in both the iron and the constantan conductors, a compensating Bowden-constantan couple was built into the circuit. The parasitic voltage due to the Bowden-iron junctions were negligible, but tests made with the Bowden-constantan compensator junctions out of action showed that appreciable errors would have occurred without the compensation. Therefore, when subsidiary junctions are introduced into a circuit where differences in temperature may exist, these should be carefully insulated and protected against the reception of heat. A few results of piston temperatures at 42·8 b.h.p. are shown below.

	Cast iron 1, °C	Cast iron 2, °C	Aluminium, °C.
Estimated surface temperature at centre	420	453	253
Estimated surface temperature at edge	305	339	232

It is seen that no great difficulty has been experienced in carrying the leads from thermojunctions embedded in the moving piston of an open frame internal combustion engine running at moderate speeds of rotation. Although a lead might break occasionally in the neighbourhood of the points of bending this should not occur frequently under such conditions. With completely enclosed engines running at high speeds of rotation the problem of carrying leads from the

moving pistons to a stationary point outside the engine is not capable of so easy a solution. In the first place the forces of inertia are greater and the pistons are usually of relatively small diameter and do not allow much room for carrying leads inside the pistons.

Professor A. H. Gibson * gave accounts of several series of tests on high-speed petrol engines where the method adopted for estimating the temperatures of the piston crowns at predetermined points was to run the engine at the required load long enough to attain steady temperatures and then to stop the engine as quickly as possible, take out the ignition plugs, and press preheated insulated thermojunctions into metallic contact with the piston crowns through the plugholes. Readings would be taken over a period of time as the pistons cooled and the original working temperatures at zero time were deduced by extrapolation.

Professor Wright Baker † succeeded in using inserted thermojunctions to measure the piston temperatures in one cylinder of a three-cylinder Mirrlees-Ricardo single sleeve valve oil engine. The cylinder bore was $5\frac{5}{8}$ in. and the stroke $6\frac{1}{4}$ in. The maximum running speeds were 1200 r.p.m. with cast-iron pistons and 1400 r.p.m. with pistons of light alloy. The nominal output was 60 b.h.p. at 1200 r.p.m. The cylinder head was of the Ricardo "Vortex" type having a central vortex chamber $2\frac{1}{2}$ in. diameter and 2 in. high. At the top of the stroke the flat crown of the piston closed the lower end of this chamber except for the small clearance between the piston and the head. The centre line of the oil injector was situated parallel to but about 1·2 in. out of the centre line of the cylinder, and delivered the oil into the vortex chamber. The cast-iron sleeve valve was 0·215 in. thick, and was given an elliptical motion at half engine speed and of major and minor axes $3\frac{1}{8}$ in. and $1\frac{3}{8}$ in. to control the admission and exhaust of the gases. Three pistons were used in the tests—one of cast-iron, one of L8 alloy, and one of Y alloy.

The thermojunctions for the cast-iron piston were of iron

* "Piston Temperatures and Heat Flow in High-Speed Petrol Engines," *Proc. Inst. Mech. Engs.*, No. 2, 1926, p. 221.

† "Piston Temperatures in a Sleeve Valve Oil Engine," *Proc. Inst. Mech. Engs.*, Vol. 135, 1937, p. 35.

and "Eureka" (constantan) wires both screwed into the piston at each point of measurement, viz.: five in the piston crown, one in the landing above the top ring, one behind the second ring, and one in the skirt on the thrust side of the piston. In the case of the light alloy pistons a complete

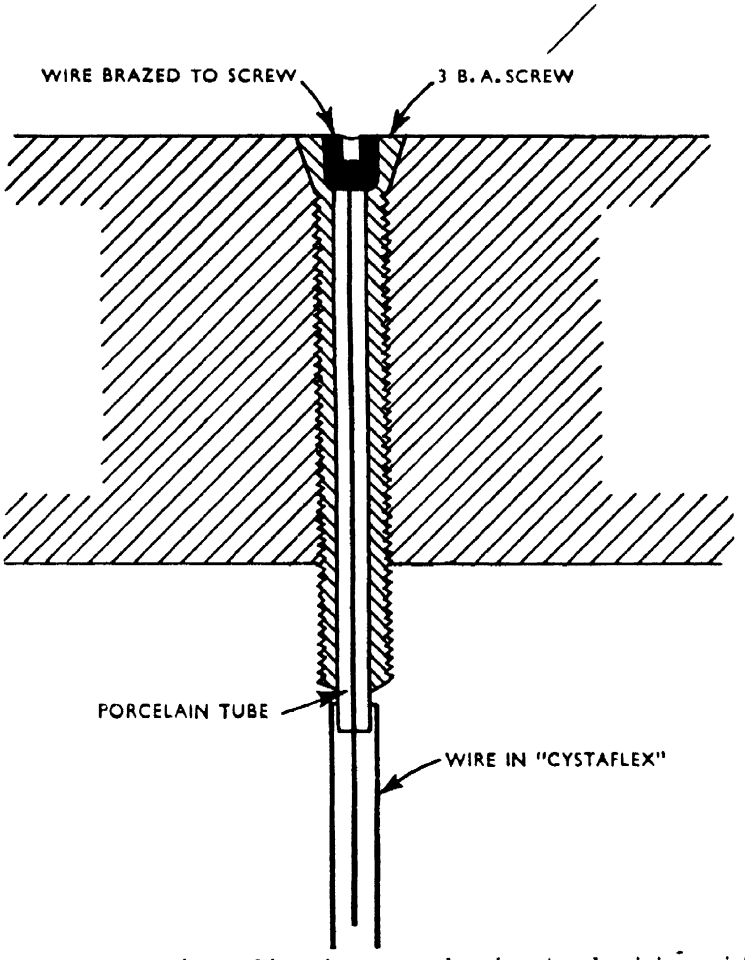


FIG 94.—Method of attaching thermocouple wires to aluminium pistons.

thermoçouple of copper and Eureka metal was used in the centre of the piston only, while for the other points in these pistons use was made of the thermopotential properties of couples formed of Eureka and the actual metal of the piston, which was found to be closely akin to copper in this respect. By attaching Eureka wire to these secondary points and completing the circuits through the Eureka wire at the centre,

the differences of temperature between the piston centre and the other points were obtained. One advantage of this method was the larger number of points of measurement for which

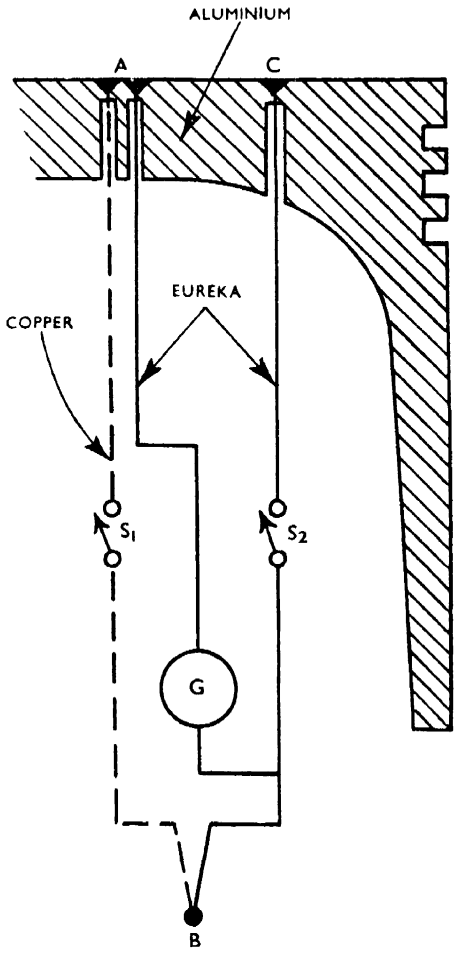


FIG. 95 —Circuits for thermocouples in piston

A Primary hot junctions of copper-eureka-aluminium.
B Primary cold junction ; copper-eureka in ice.
C Secondary cold junction (eureka-aluminium).
G Galvanometer.
S_1 closed and S_2 open : galvanometer reads temperature difference between points A and B.
S_1 open and S_2 closed : galvanometer reads temperature difference between points A and C.

leads could be accommodated in the piston. The method of attaching the thermocouple wires to the aluminium alloy pistons is shown in Fig. 94, while the scheme of the thermocouple circuits is represented in Fig. 95.

The most difficult problem which had to be solved in relation to the piston couples concerned the carrying of the leads from the mouth of the piston to the required stationary point outside

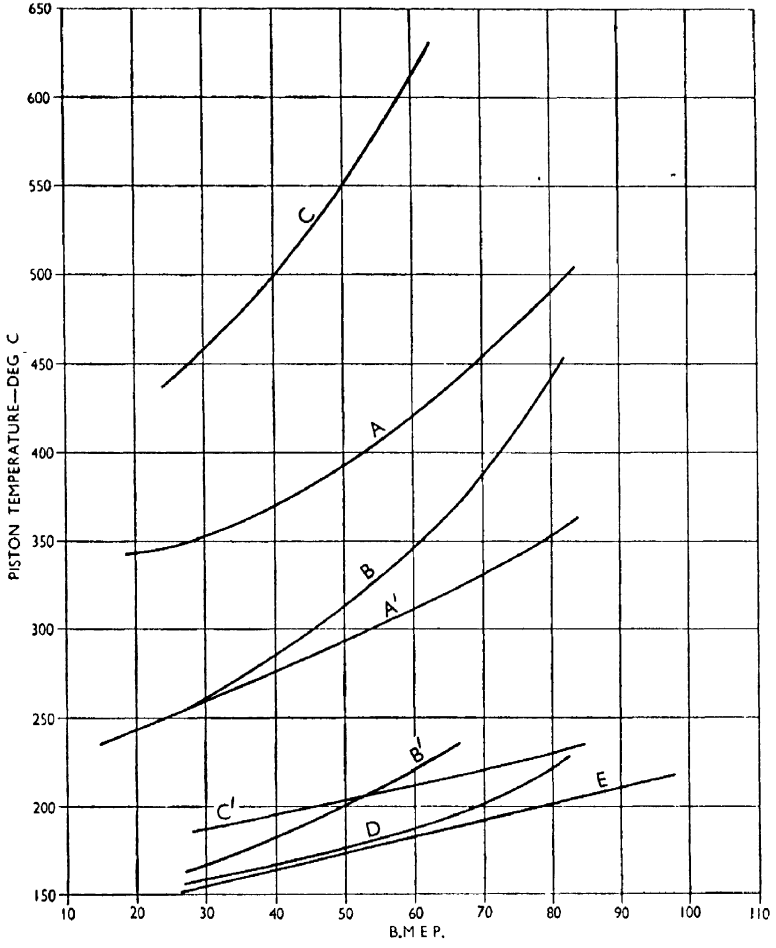


FIG 96.—Effect of variations in brake mean effective pressure.

A and A′ Centre and edge temperatures for 12-in. cast iron piston No. 2; mean cylinder temperature, 42° C.
B and B′ Centre and edge temperatures for 5⅝-in. Mirrlees-Ricardo cast iron piston; mean cylinder temperature, 90° C.
C and C′ Centre and edge temperatures for 14-in. cast iron piston (Mucklow).
D Centre temperature Mirrlees-Ricardo "L8" alloy piston (No. 1).
E Centre temperature, J.A.P. petrol engine running at 3000 r.p.m.

the engine. A small double linkage carried the leads from the clamped position at the mouth of the piston to a point on the connecting rod The leads were then carried to the big end of the connecting rod, then along the arms of a double

linkage connecting the big end with a stationary stud in a casing bolted in place of the crank-case cover. The various links were so proportioned as to subject the wires at the pivots or hinges to as little bending as possible. At the six points of bending for each lead a piece of clock spring, 0·005 in. × 0·066 in. section, was inserted in each lead with the two ends of each spring arranged close together so as to be at the same temperature and therefore reduce as much as possible the effect of any parasitic currents at the connections of the springs and the wires. It was found necessary to clamp all the leads, which were of No. 22 I.W.G. encased in " Cystaflex " tubing, at points not exceeding 1½ in. apart, and to secure them further against vibrations by cementing them in position with heavy coatings of " Durofix " Excessive flutter of the loops of spring at the hinges was prevented by ebonite dampers set to control the maximum displacement.

The results shown in Fig. 96 on a brake M.E.P. base in lb. per sq. in. refer to the piston crown temperatures in the oil engines so far considered, together with the temperatures at the centre of the piston of a J.A.P. petrol engine running at 3000 r.p.m. In some cases the actual point of highest temperature may not coincide with the centre of the piston owing to departure from symmetry in the design, or to the working conditions of relatively cold inlet and hot exhaust, or to the position of the injection valve. The general laws of the conduction of heat suggest that the difference of temperature between near the centre and the edge of the piston crown is lower the greater the conductivity of the material, the smaller the diameter, and the thicker the metal. In general, then, the aluminium alloy piston is cooler than the cast-iron piston of the same size, and a small piston is cooler than a large one of the same general design. The high temperature of the centre of piston C was specially mentioned on p. 193.

Experiments were made on a Dorman-Ricardo two-cylinder compression-ignition engine by W. L. Bride, M.Sc.Tech.,B.Sc.* The cylinder diameter was 4·72 in. (120 mm.) and the stroke 7·08 in. (180 mm.), and the engine generated 37 b.h.p. at

* " Piston Crown Temperatures in a Compression-ignition Engine with Comet Head," *Proc. Inst. Mech. Engs.*, 1943, Vol. 150, No. 4.

1500 r.p.m. The piston tested was of Y alloy and had a flat crown fairly heavily ribbed to the gudgeon pin bearings. The number of leads in the piston was limited to seven. The thermojunction in the centre of the crown was formed by constantan-nichrome wires while the remaining five points were each connected to a single wire of constantan, and the temperatures at these points were obtained from the potential differences set up between these points and the constantan wire at the centre. All the junctions were calibrated against standardised mercury thermometers. The potentiometer method was used to measure the e.m.f. of the couples. The thermocouple wires were brazed into cheese-headed 2 B.A. brass screws, the latter being then screwed into the piston crown and the cheese head filed off flush. The other end of the wires were soft soldered in holes in steel contacts in an ebonite block fixed at the bottom of the piston skirt, following a previous successful application of this method.* When these contacts approached the bottom dead centre they made contact with corresponding insulated spring-loaded plungers fitted in small cylinders fixed to the inside of the crank-case, with the period of contact about 34° of the crank-shaft rotation. From these plungers the wires were led to the temperature measuring apparatus. To keep the insulated wires in place inside the piston they were clipped with soft wire passed through small holes drilled behind the oil rings and finally covered with "Durofix." The bottom plunger contacts were spring loaded with springs of stiffness requiring 7 lb. to compress $\frac{1}{8}$ in.

Fig. 97 indicates the temperatures obtained at 1200 r.p.m. with the cooling water outlet at 71° C. It is seen that the temperatures over these points on the piston did not differ much, especially at full load, but were much higher than were recorded in the Mirrlees-Ricardo engine as curve D in Fig. 96. The curves of temperature A to D in Fig. 97 refer to the liner temperatures measured by thermojunctions, C being the highest and B the lowest points in the liner where measurements were made. Point C was about $1\frac{1}{2}$ in. below the cylinder head flange.

The space available inside the casings of high-speed petrol

* "Symposium on Piston Temperatures," *J. Soc. Automotive Eng.* (*U.S.A.*), 1939, Vol. 44, No. 2.

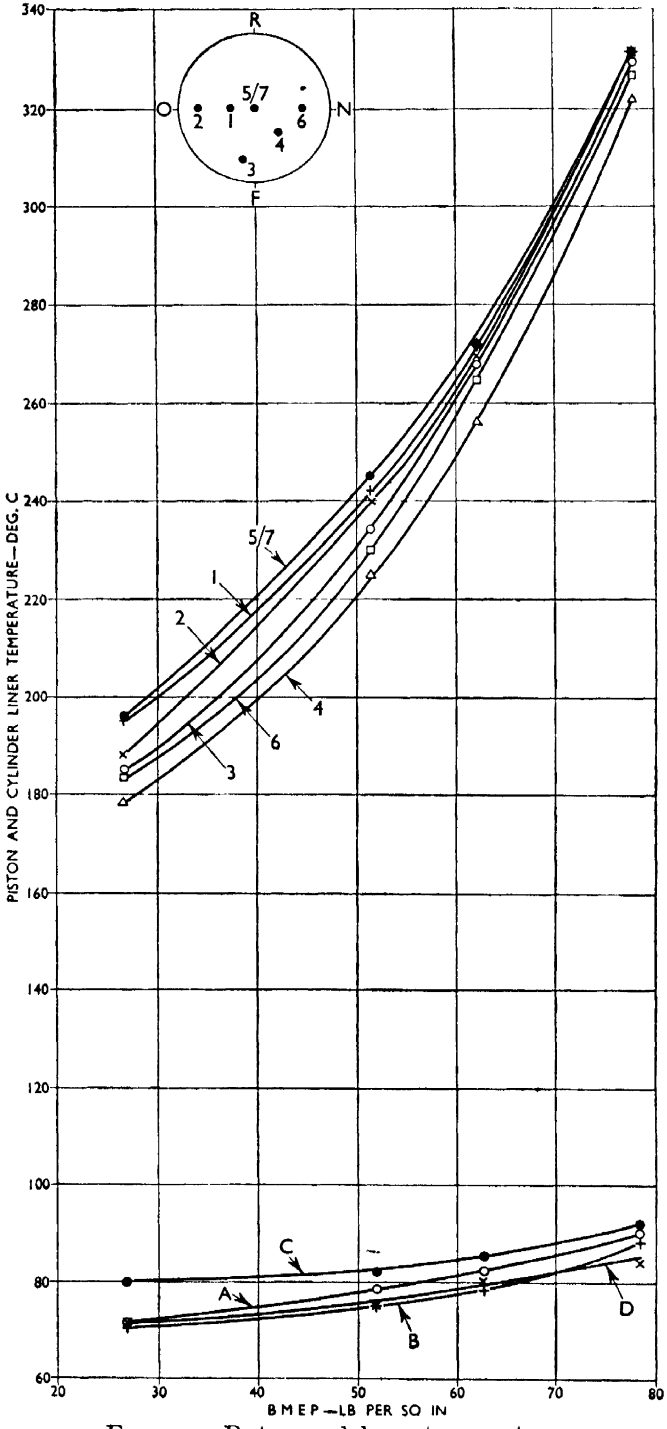


FIG. 97.—Piston and liner temperatures.

engines may be too limited to allow of the adoption of the methods so far described for carrying electrical wires from a moving piston to the outside electrical measuring instruments. A method of carrying thin electrical wires through the crown of the piston and the cylinder head was described in the paper * referred to below. In these particular experiments the problem was to measure the axial and radial movements of the top piston ring of a single-cylinder air-cooled petrol engine under experimental conditions. The maximum axial movement of the ring was 0·003 in. and was measured by a strain gauge made of copper-nickel wire 0·0015 in. diameter. This movement gave a variable tensile strain in the wire and caused a corresponding variation of the electrical resistance, measured or indicated on an oscillograph. To carry the leads from the moving piston to the outside electrical instruments a high tensile steel tube $\frac{3}{16}$ in. diameter was screwed into the crown of the piston and passed through a reamered hole in the cast-iron cylinder head with a radial clearance of 0·001 in., which allowed not more than a negligible leakage of gas. The upper end of the steel tube was attached to a small grooved phosphor-bronze guide block sliding on two case-hardened steel guides. Pivoted to the upper end of the tube was a floating duralumin beam with the other end of the beam pivoted to a short swing link. One lead of the strain gauge in the piston was earthed to the piston and the other lead connected to an asbestos-insulated wire which passed up through the steel tube and was cemented in the tube. From there the wire was connected to a length of thin steel piano-wire which was led along the beam and the swinging link until it reached one of the terminals. A second length of piano-wire connected the upper end of the steel tube to the second terminal to make the circuit continuous without relying on the piston being earthed through its sliding surfaces. At each of the three joints in the linkage the piano-wires lay in grooves cut in a bobbin of insulating material. Radial collapse of the ring was similarly indicated by contacts made in the ring gap.

Information is given in the paper of cements suitable for

* "Piston Ring Movement during Blow-by in High-speed Petrol Engines," by P. Dek Dykes, M.A., Ph.D., A.M.I.Mech.E., *Proc. Inst. Mech. Engs.* (*Auto. Div.*), 1947–48, Part II.

cementing the glass insulating tubes in position in the piston, and of the cementing of the wires into the glass tubes. The thin wire loop forming the strain gauge had a resistance of 70 ohms and was supplied with 30 milliamperes d.c. from a 12-volt accumulator through a 330 ohms non-inductive resistor. The potential differences across the loop were amplified by a commercial amplifier, said to give a nearly constant voltage gain of 7000 at frequencies between 0·1 and 40,000 cycles per second. Two cathode ray oscillographs were used, one oscillograph being observed visually and the other was photographed by a camera with the film fed at constant velocity. The two time-bases were triggered at the start of each compression stroke of the engine by an electro-magnetic "pick-up" on the engine cam shaft, and gave one sweep during every two revolutions of the engine. The photographic oscillograph was modulated so that the screen was normally dark, but at regular intervals a single stroke of the time-base gave a bright trace on the screen. This arrangement avoided over-lapping of records on the photographic film.

In these particular experiments it was never necessary to run the engine longer than about 15 minutes at a time, and this method of maintaining the electrical connections with the piston proved to be adequate for these conditions up to nearly 6000 revolutions per minute. If the same method were to be used for carrying electrical wires for measuring piston temperatures it would probably be necessary to modify the connection of the sliding steel tube to the piston crown so as to give as little disturbance as possible to the normal path of the heat flow in the piston.

Messrs. Callendar and Nicolson made experiments on the rate of condensation of nearly air-free steam at the temperatures usually obtained in steam engine cylinders, using a thick-walled condenser about 24 in. long with mercury thermometers inserted in holes bored in the metal. They found that the rate of condensation was not appreciably altered by using revolving brushes to sweep over the condensing surface five or six times per second, and they concluded that the maximum rate of condensation, h_s, was about 0·74 B.Th.U. per sq. ft. per sec. per deg. Fahr. difference of temperature between the steam and the wall. They also deduced the thermal conductivity of the cast iron.

In the same report of the British Association * the late Professor Callendar described some experiments made on the condensation of air-free steam on the outside of a platinum tube of $\frac{1}{4}$ in. bore, 16 in. long, and 0·006 in. thick, with condensing water flowing through the tube. The platinum tube was enclosed by an outer tube of brass or of glass. The mean temperature of the platinum tube was determined by measuring the electrical resistance of the portion of the tube on which the steam condensed. The difference of temperature between the two sides of the thin platinum tube itself did not exceed $\frac{1}{4}$° C. With a short length of condenser, and free escape of steam to the atmosphere from the bottom of the condenser set vertically, the rate of condensation h_s was 0·78 B.Th.U. per sec. per sq. ft. of tube surface per deg. Fahr. difference of temperature between the steam and the tube. With the same conditions, but with nearly twice the length of tube exposed to the steam, h_s was 0·88 to the same units. The value of h_s was rather greater with the flow of steam upwards. This was ascribed to the effect of the increased surface due to drops and rivulets of water.

A copper-constantan thermocouple was used by H. P. Jordan,† working under the late Professor J. T. Nicolson, to determine the temperature of a copper tube through which heated air was flowing, the tube being cooled by water circulated on the outside of the tube. The particular arrangement of the thermocouple is shown in Fig. 98. First, a steel, or in some experiments a gun-metal, sheathing S, was screwed up tight, till its knife-edge end had made a watertight joint with the internal copper air-pipe, and thus excluded the water from this portion of the pipe. Into this sheathing was screwed a long copper plug P, with two longitudinal slots in which were laid the insulated copper and constantan wires W. To the copper plug was keyed a hollow vulcanite end V, so that copper and vulcanite turned together. The end of the vulcanite was solid and turned down to fit into a small recess of $\frac{1}{8}$ in. diameter drilled to a depth in the metal of the copper pipe equal to half its thickness. Two small pinholes were drilled through the small end of the vulcanite. The insulated copper and constantan wires were laid in the slots in the

* Section G, 1897. † *Proc. Inst. Mech. Engs.*, 1909, p. 1317.

copper plug, and then brought inside the vulcanite end. For a short distance (about $\frac{1}{4}$ in.) at their ends the wires were stripped of their insulation, and this length was pushed through

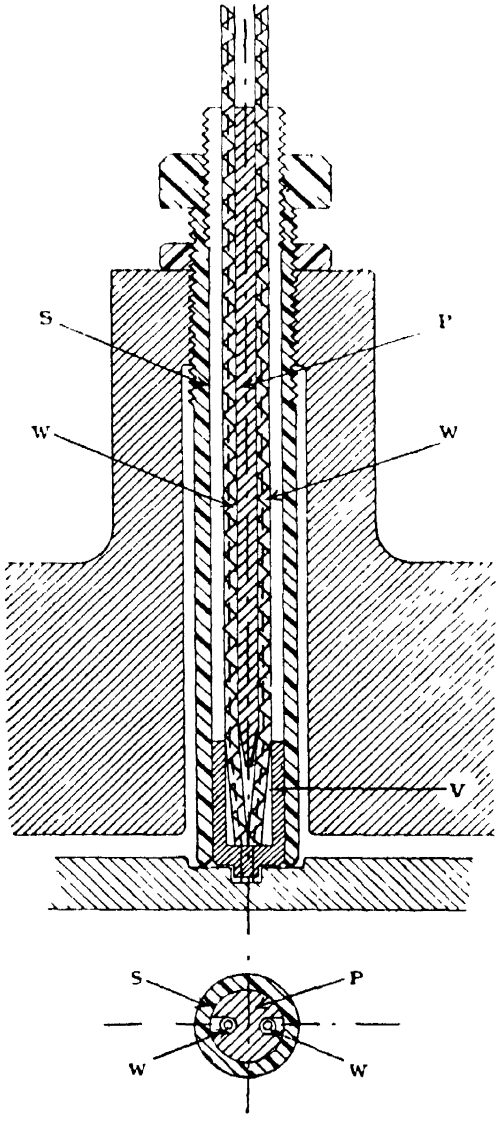


FIG. 98.—Arrangement of thermojunction for temperature of copper tube.

the pin-holes in the small end of the vulcanite, thus leaving the two ends standing out from about $\frac{1}{64}$ to $\frac{1}{32}$ in. and about $\frac{1}{20}$ in. apart. The wires were then fixed in the slots by shellac.

To make the junction, the copper plug was carefully screwed up until it was felt that the end was fitted well up against the internal pipe. Great care was taken that the small vulcanite end should fit into the recess in the metal of the pipe; this was done by testing, with a gauge and cutter, the exact size of the vulcanite end before fitting in the junctions. The cold junction was kept at a constant known temperature by means of an oil-bath.

The direct deflection method was used to measure the e.m.f. produced by the difference of temperatures of the hot and cold junctions, the galvanometer being of the moving coil mirror type. The deflections on the galvanometer scale were carefully calibrated by keeping one junction in a cold oil-bath of constant temperature and heating the other junction in a second oil-bath by means of a Bunsen burner, the temperatures of both oil-baths being taken by standard mercury thermometers. From these results a curve was drawn connecting temperature differences of the junctions with the galvanometer deflections. By the aid of these curves the metal temperatures were inferred from the galvanometer deflections observed during the course of the experiments. An objection to this particular arrangement of the thermo-junctions might be urged on account of the appreciable surface of the tube which is excluded from contact with the water by the sheath S which might affect the temperature at this point. There does not appear to be any reason why the sheath should not be reduced in diameter in the neighbourhood of the junction and the vulcanite end V made to suit.

Although this arrangement is suitable where the temperature of the tube is comparatively low there is likely to be some difficulty in keeping the joint between the tube and the end of the sheath tight against leakage when the tube has a relatively high temperature, because of the larger relative expansion between the copper tube and the cast-iron body of the apparatus.

The arrangement shown in Fig. 99 was devised by Professor A. L. Mellanby and used by G. C. Webster.* The copper and constantan wires forming the thermocouple are not shown in

* "Condensation of Steam," *Trans. Inst. Engs. and Shipbds. in Scotland*, Vol. LVII, 1913–14.

the illustration, but they passed down the centre of the steel sheath to make contact with the copper tube. These wires were caulked into holes in the tube about $\frac{1}{16}$ in. deep, the ends of the wires being swelled slightly to get a good contact in the holes. To enable this to be done easily the steel sheath shown in Fig. 99 was made in two parts, the bottom part brazed on to the copper tube and the upper part screwed into this bottom part. A nut at the top formed a steam tight joint flexible enough to allow for the relative expansion of the tube, and at the same time kept all parts of the sheath pressed downwards to minimise the danger of leakage into the centre of the

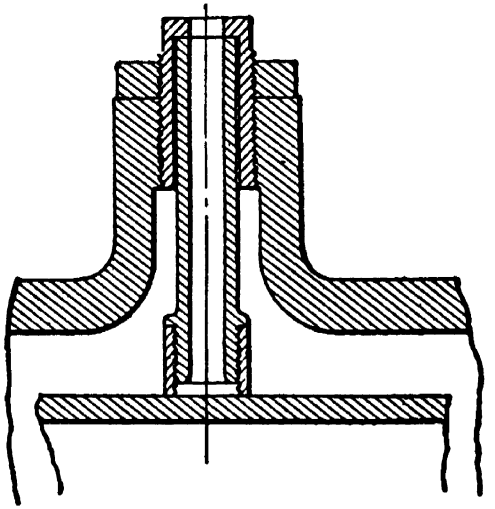


FIG. 99.—Arrangement for shielding thermojunction in copper tube.

sheath. It would be noticed that this arrangement excludes a certain small portion of the outside of the tube from contact with the steam, but the method of calibrating the thermocouples minimised the possibility of errors from this cause. In the actual apparatus a connection with a shut-off cock between the steam and water inlets was provided. The water outlet could also be connected to another condenser so that steam or hot water could be passed through on both sides of the tube when required for calibration purposes. By this means both sides of the copper tube could be flooded with steam or hot water, arranged to flow through at a sufficient rate to keep nearly a constant temperature at all parts of the

tube. This temperature was observed by calibrated mercury thermometers placed in pockets at the inlet and outlet, and thus the tube temperature was known fairly accurately during the calibration.

The potentiometer method of measuring the electromotive force was adopted.

Before the arrangement for the thermojunctions shown in Fig. 99 was adopted one was tried of the type used by Mr. Jordan, Fig. 98. With the comparatively high tube temperatures obtained, however, there was so much trouble with the leakage of steam under pressure, probably due to relative expansion of the condenser tube, that the arrangement had to be discarded in favour of that shown in Fig. 99.

It may be of interest to note that the steam pressure in these experiments was varied from about 90 to 19 lb. per sq. in. abs. On the average the rate of condensation h_s at the latter pressure was about 20% greater than at the former pressure. The value of h_s also increased with the rate of steam flow w_s through the steam space. If w_s is taken to be the arithmetical average of the weight of steam entering and leaving the apparatus, then with w_s equal to 1 lb. per sec. the average value of h_s was about 0·5 B.Th.U. per sq. ft. per sec. per deg. Fahr. difference of temperature between the steam and the tube, while h_s was about 0·8 with w_s equal to 6, both to the same units as before. Estimates were also made on the rate of heat transmission on the water side for water velocities from 1 to 14 ft. per sec.

E. M. Bryant * used thermojunctions to measure the temperature of metal plates forming the bottom of a small boiler evaporating water at atmospheric pressure. After trying various arrangements that shown in Fig. 100 was finally adopted as causing the least disturbance to the flow of heat through the metal. A small plug of circular section, of the same metal as the plate, was made to fit into a slightly tapered hole so that its ends were level with the surfaces of the plate. Two holes, $\frac{1}{16}$ in. in diameter, were drilled lengthwise on opposite sides of the plug to the desired depth, and they were connected by a horizontal hole of the same diameter. There were six such plugs arranged in a circle of $1\frac{1}{4}$ in. radius round

* *Proc. Inst. Civil Engs.*, Vol. CXXXII, 1897–98.

the centre of the plate and at various depths in the metal. The junction formed a bead fitting loosely into the horizontal hole in the plug, and was fixed in position by solder. The remaining space in the holes was filled up with very fine Portland cement. A little rubber solution was used between the plug and the plate to ensure its being watertight. The connecting wires from the junction were covered by asbestos within the holes, and enclosed within rubber tubes, passed directly through the water.

The e.m.f.s of the thermojunctions were measured by means of a moving coil galvanometer which could be read to 0·2° C.

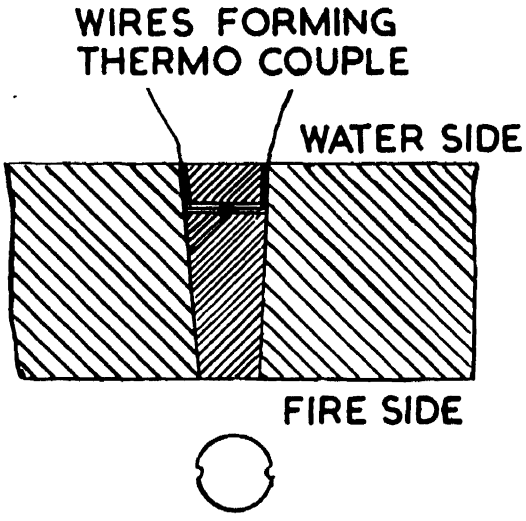


FIG 100.—Plug in boiler plate containing thermojunction.

A calibration curve was drawn for each junction, using the known boiling points of steam (212° F.), aniline (363° F.) and naphthalene (424·5° F.).

In the Technical Paper No. 114, issued by the Department of the Interior, Bureau of Mines, Washington, U.S.A., experiments are described in connection with the measurement of the temperature of boiler tubes and the transmission of heat. Copper-constantan thermocouples were used embedded in the metal of a tube in the bottom row of tubes in a water-tube boiler where the hot gases entered among the tubes on the outside. A couple was also placed in a tube in the highest row where the gases left the boiler. The arrangement of the

thermojunctions is shown in Figs. 101 and 102. The hot junctions were formed by embedding the constantan and copper wires separately in the metal of the tube, and the method adopted for fixing these wires in the metal is shown in Fig. 103. A hole was drilled in the tube to a depth of about $\frac{1}{16}$ in. and about 0·001 in. larger in diameter than the wire, and the end of the wire was then pinned in with the special hollow tool having a cup-shaped end as shown in Fig. 103. Two or three light taps with an 8-oz. hammer were sufficient to pin the

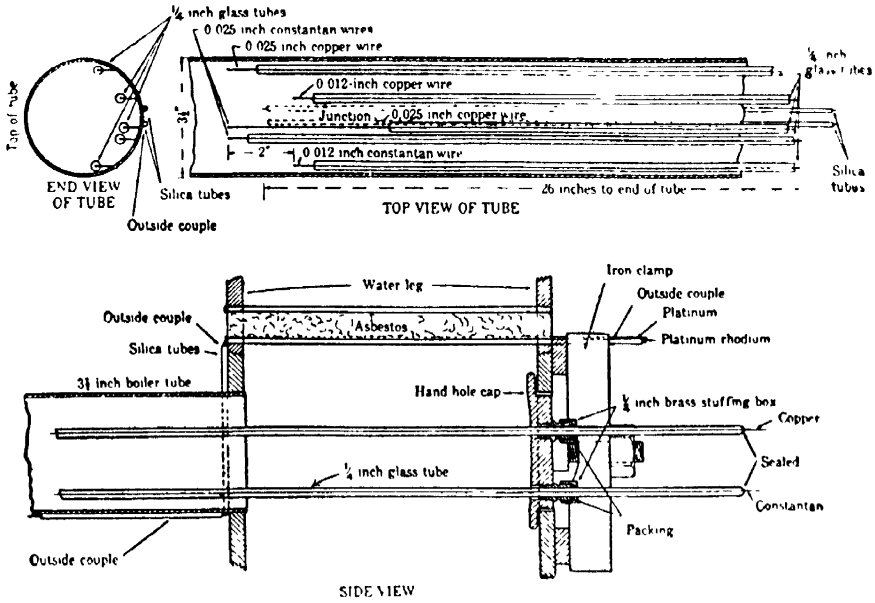


FIG 101.—Arrangement of thermojunctions in boiler tube.

wires in the tubes so tightly that the wire would break rather than pull out of the hole. The thermocouple wires on the inside of the tube were at first insulated by being passed through thick-walled ¼-in. glass tubes, which passed through brass stuffing boxes fitted in the hand-hole cover opposite the boiler tube. The hole in the glass tubing was so small that leakage of steam and water was insignificant. It was found, however, that the glass tubing was attacked by the boiler water and gradually it became soft and opaque, and disintegrated after about five days' usage. In later experiments small porcelain tubes were used and it was found that these were not appreciably affected by the boiler water and steam.

The couples on the outside of the boiler tube were of platinum, platinum-rhodium wires insulated by silica tubes.

The method of measuring the difference of temperature

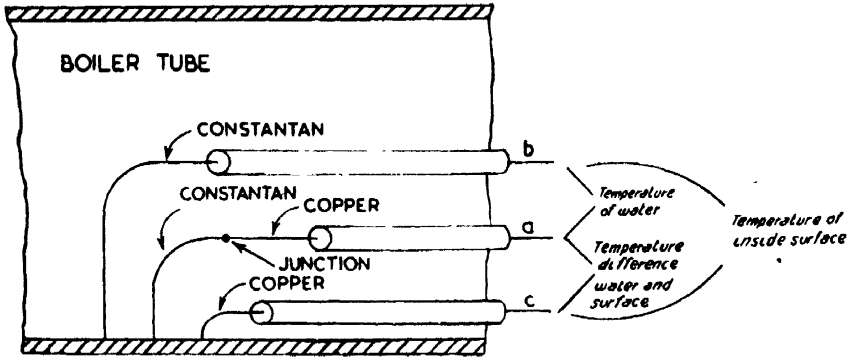


FIG. 102.—Diagrammatic arrangement of thermojunctions in boiler tube.

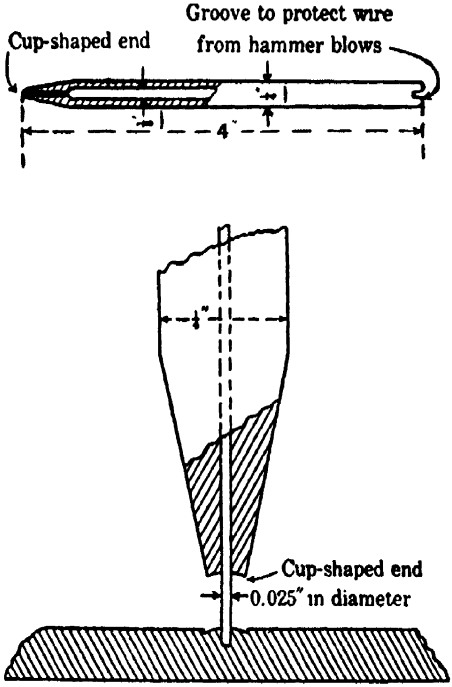


FIG. 103.—Method of fixing wires of thermojunctions into boiler tube.

between the inside surface of the boiler tube and the water is illustrated diagrammatically in Fig. 102. By using the wires (*b*) and (*c*) the temperature of the metal was obtained while

(*a*) and (*b*) gave the temperature of the boiler water, the two constantan wires in the metal then being neutral. In both these cases the cold junction was at any convenient place and temperature outside the boiler. Using (*a*) and (*c*) gave the difference between the temperature of the metal (hot junction) and the boiler water (cold junction). In all cases the e.m.f. was obtained by the potentiometer method. The temperature of the boiler water was also observed independently by a couple formed of a closed ¼-in. copper tube having a constantan wire fused in the closed end. The results obtained with this couple compared very closely with those obtained with the wires (*a*) (*b*) in Fig. 102.

To ascertain the effect of electrical leakage and galvanic action of the boiler water where the leads passed through the boiler water as in Fig. 101, special experiments were made by fixing two copper and two constantan wires into an iron strip in the manner described on p. 211, thus forming two thermocouples. The leads of one thermocouple were taken through a 3-in. test pipe and brought out through the cap in a manner similar to that used for the boiler thermocouples, the length of this pipe being arranged so that the leads were surrounded by water for about the same length as in the boiler tube. The leads of the other thermocouple were in air. Before any water was run into the pipe a calibration was made, showing that the two couples read exactly alike. Hot water from the boiler was then circulated through the test pipe so that the same water and pressure were used as in the boiler tube. It was found that the readings of the thermocouple with the leads immersed in the pipe were 0·12 to 0·15 millivolt too high when the true potential generated by the couple was about 7 millivolts, and this was equivalent to a temperature reading too high by about 3° C. Hence 3° C. was subtracted from the temperatures indicated by the thermocouples in the boiler tube to give the true temperatures. Probably the most important feature shown by these results was that the temperature of the tube was within 10° F. to 20° F. of that of the boiler water.

The fusion points of metal alloys have also been used to estimate the temperature of heating surfaces, as, for instance, that of the heating surface of boilers. In this method the

alloys of various melting temperatures are inserted a good fit in holes sunk in the boiler plate or tube and the temperature of the plate is taken to lie between the melting point of the last one to fuse and the next higher in fusing temperature which remains solid. Sir A. J. Durston, for instance, used this method to estimate the temperature of the heating surfaces at various points of a model boiler.* The method, however, is now considered to be somewhat crude, and much inferior to thermojunctions under skilful manipulation.

* *Trans. Inst. Naval Arch*, 1893.

CHAPTER VIII

THE MEASUREMENT OF RAPIDLY FLUCTUATING TEMPERATURES

It is well known that the inner surface of the cylinder of a reciprocating steam engine or internal combustion engine fluctuates in temperature in response to the varying temperatures of the fluid near to or in contact with the surface. This fluctuation of the surface temperature, however, is comparatively small, and does not penetrate far into the metal. Mr. Bryan Donkin * attempted to measure the range of fluctuation of temperature in a steam engine cylinder by using very delicate mercury thermometers of small diameter inserted in holes at various distances from the inner surface. Although he observed a fluctuation of temperature near the surface this method was not successful on account of the appreciable lag of the thermometers.

Thermojunction methods were tried by Professor E. Hall of Harvard College,† but with limited success. Professors Callendar and Nicolson ‡ seem to have been the first experimenters to use thermojunctions successfully for the measurement of the fluctuation of temperature in the cover of a steam engine cylinder. They experimented on a small single-cylinder engine, having a cylinder diameter 10·5 in. and stroke 12 in. with a balanced slide valve controlled by a crank-shaft governor, and for the purpose of the experiments the engine was made single-acting by the addition of a brass lap of sufficient length to the front end of the valve. A special end cover was cast for the cylinder, well insulated, and fitted with eight thermocouples at different depths. Any one or any two of these junctions could be connected to the galvanometer and to the cold junction by a suitable arrangement of mercury cups, and a contact maker could be set to close the galvano-

* *Proc. Inst. Civil Engs*, Vol. CXV, 1893–94, Part I.
† *Trans. Amer. Inst. Elect. Engs.*, Vol. VIII, 1891.
‡ *Proc. Inst. Civil Engs.*, Vol. CXXXI, 1897–98, Part I.

meter circuit at any point of the stroke and for any desired fraction of a revolution.

The e.m.f. of the thermocouple was balanced against that of a steady current flowing in a uniform potentiometer wire. In the first arrangement the external or "cold" junction was formed in a piece of cast iron, cast from the same ladle as the cylinder cover, and was maintained constantly at or very near 212° F. in a paraffin bath by means of a jacket of steam at atmospheric pressure. It was soon found that the cyclical fluctuations of temperature in the wall were so small that difficulty was experienced in getting consistent readings over any lengthy period of time because of the small incidental changes in the mean wall temperatures which nearly always occurred during the time required for complete observations on all the thermojunctions. The thermo-electric circuit was then modified and consisted simply of the "hot" junctions as before, with the "cold" junction formed in the metal of the cover at a point where there were no cyclical variations of temperature, having the same mean temperature as the "hot" junctions. By this means only the momentary small difference between the hot junction and the mean temperature of the metal was observed, for which the thermojunction method is admirably suited. Nearly all the troubles that otherwise arose from the slow changes of temperature conditions were thus avoided, since a gradual change of temperature would affect the metal at a depth of $\frac{1}{2}$ in. practically to the same extent as at the surface of the metal.

The cylinder cover was provided with a steam-tight jacket. Eight holes for the junction wires were bored to various depths, leaving from 0·01 in. to 0·64 in. thickness of metal measured from the inner surface and arranged in a circle of 1·5 in. radius round the centre of the cover. The thermocouple wires were insulated with mica and india-rubber tube and washers, except at the bottom of the holes where they made contact with the cast iron of the cover. In passing through the jacket they were protected by steel tubes screwed and soldered into the metal of the cover. A central tube was also provided in the cover for the clearance of a platinum resistance thermometer carried by the piston to measure steam temperatures during the cycle.

Commercially pure nickel was first tried against the cast iron of the cover, but the e.m.f. was found to be much less than with wrought-iron wire. All the iron wire used was from the same hank and carefully annealed after being bent into position. At first the iron wires were pressed against the bottom of the holes in the cover to form the junctions. Subsequently all the junctions were carefully soldered with pure tin to ensure complete and permanent thermal contact between the wires and the cover. Fig. 104 represents the arrangement of the thermojunctions in the cylinder cover.

A set of eighteen thermojunctions were also fitted along the side of the cylinder to observe the wall cycles and the distribution of temperature along the barrel surface.

The cycle contact-maker on the engine crank-shaft closed

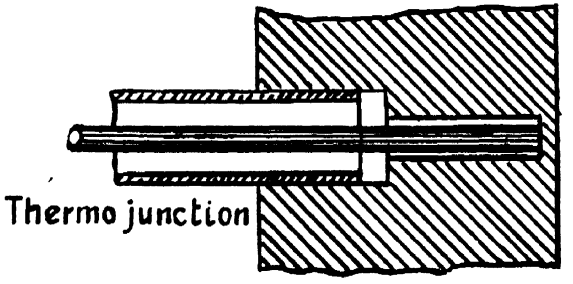


FIG. 104.—Callendar and Nicolson's arrangement of thermojunctions in cylinder cover.

the galvanometer circuit for any selected thermojunction for a small fraction of a revolution at any desired point of the cycle. A pair of insulated revolving brushes were connected by a copper wire, and one brush made contact with a central copper tube whilst the other made contact with a number of copper sectors of different lengths let into the circumference of a wooden disc. A galvanometer circuit could thus be closed by any of these sectors so as to alter the duration of contact. The point of the cycle at which the brush made contact was determined by the setting of a divided circle. The contact-maker could be inserted in the circuit of either of two galvanometers according to the desire to observe a steam cycle with the platinum thermometer or a wall cycle with one of the thermocouples.

The cylinder steam thermometers were of the platinum

resistance type made of very fine platinum wire 0·001 in. in diameter. One thermometer was fixed in the central hole in the cylinder cover from which the first observations of steam temperatures were obtained. A comparison of the recorded steam temperatures throughout the whole cycle with the corresponding saturation temperatures deduced from the indicator diagram pressures showed that the steam in the hole in the cover was rather highly superheated throughout nearly the whole cycle. Another platinum resistance thermometer was then fixed in the piston as shown in Fig. 105, from which it is seen that compensating leads C were used as described on p. 41. There were the four leads of thick platinum wire

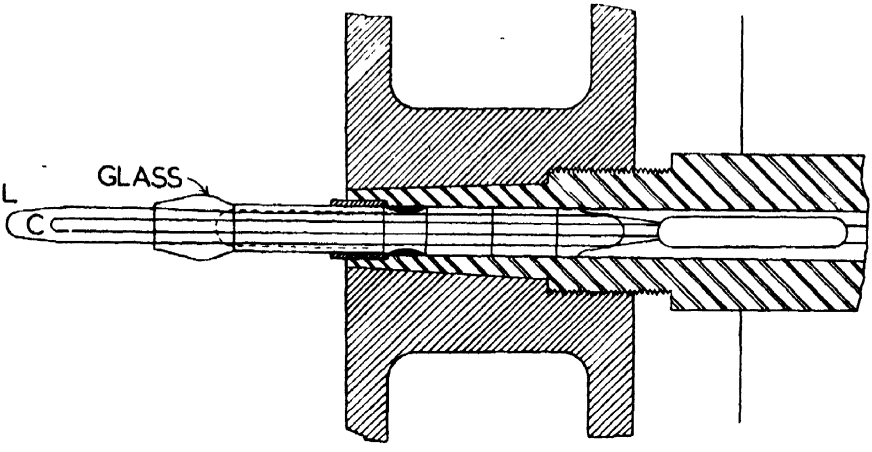


FIG. 105.—Platinum resistance thermometer in steam engine piston.

fused into a glass tube at both ends. In the middle of the tube a constriction was formed by melting in the glass so that it was very thick at that point. The leads which came out at the end were connected to the wires leading to the measuring apparatus. The constriction was fitted into a gland with asbestos packing, the object being to prevent the steam pressure from blowing the thermometer out of the hole. Although the central portion was made of glass it was found that it would stand the steam being turned straight on to it, and although the measuring platinum wire was only 0·001 in. diameter the wire was not broken by the rushing steam.

The diagrams in Fig. 106 show the character of the results obtained at a speed of 73·4 revolutions per minute. The full

line was derived by the aid of steam tables from the pressures given by the indicator diagram. The plain crosses are the temperatures given by the piston thermometer, from which it is seen that there is a fairly close agreement with the full line diagram. The dotted line shows the cover wall temperatures at the depth of $\frac{1}{25}$ in. from the inner face, and it is seen that at this point the range of temperature is only about 4° F. The laws of the conduction of heat may be used to estimate the probable range of temperature at the surface, and by this means the writer deduced a surface range of about 7° F.

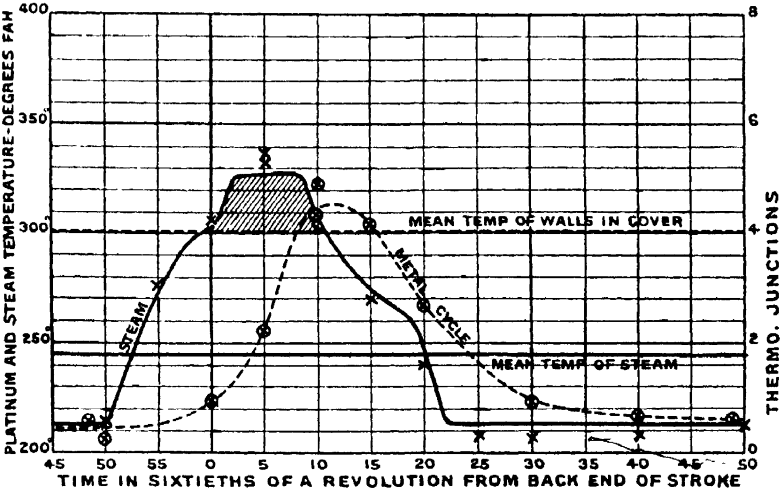


FIG. 106.—Cyclical fluctuations of temperature in steam engine cylinder.

Messrs. Coker and Scoble * used similar methods to measure the fluctuations of temperature in the metal of the cylinder, in the inlet and exhaust valves, and in the piston of a small National gas engine. The horizontal cylinder was 7 in. diameter, with the stroke 15 in. It ran at a normal speed of 240 revolutions per minute, using town's gas. The thermo-junctions were composed of cast-iron plugs screwed into the metal of the cylinder, valves, and piston, with wrought-iron wires inserted in the plugs. The form of the couple or junction used is represented in Fig. 107 in reference to the inlet valve, which was bored out axially to allow the wrought-iron leads to pass to the hollow cast-iron plug inserted in the centre of

* *Proc. Inst. Civil Engs.*, Vol. CXCVI, 1913–14, Part II.

the valve face. The inner diameter of the plug was about 5 mm. and the diameter of the wrought-iron wire 1 mm.

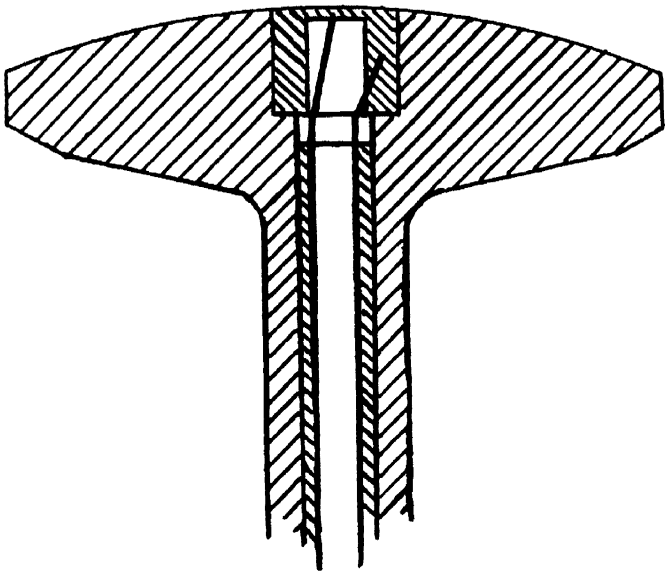


FIG 107.—Thermojunction in gas engine inlet valve.

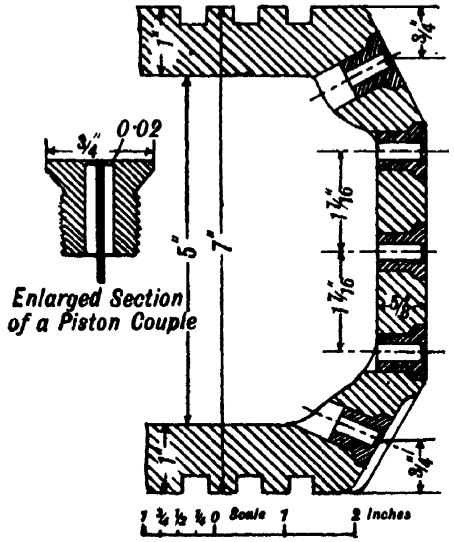


FIG. 108.—Arrangement of thermojunctions in a gas engine piston.

The thickness of the metal at the face of the plug was about $\frac{2}{100}$ in.; one wire was riveted through to the inner face and the other connected to the plug at a distance of about $\frac{1}{2}$ in.

from the inner face. Any cyclical changes of temperature would be inappreciable at the depth of ½ in. from the face, and thus only the cyclical variations of temperature at the surface of the plug were measured. In determining the mean temperatures of the metal the wire leading to the centre of the plug was used and the other not connected; the circuit was in this case completed at a convenient part of the engine frame.

The wires were insulated by two-way fireclay tubes, and in all cases the cast-iron plugs were cut from the same bar and the wires taken from the same hank. The calibration of the couples was obtained by determining the potential difference between the hot and cold junctions when one was immersed in a solidifying metal and the other in melting ice. The calibrated values did not much differ, and the following are given as an example:

Hot junction, ° C. $=t$ . . .	0	327	419	657
Electromotive force, microvolts $=e$.	15	3840	4500	6320

This corresponds very nearly to the formula:

$$e \text{ (microvolts)} = -15 + 14t - 0{\cdot}0068t^2.$$

Hence,* $$\frac{de}{dt} = 14 - 0{\cdot}0136t.$$

Five cast-iron plugs were inserted in the vertical diametral plane of the piston as is shown in the cross-section in Fig. 108. Only one wire was led from each piston couple, and a long coiled spring supplied the flexible connection required by the motion of the piston. All the iron wires were riveted into the cast-iron plugs, as represented by the enlarged section of a couple in Fig. 108, the hole in the plug being about 3 mm. in diameter. There are some possible defects in the formation of these thermocouples which are discussed later on p. 223. The differences of potential were measured on the potentiometer or bridge principle described in Chapter III on p. 70.

When determining the cyclical variations of temperature

* Sometimes called the "thermo-electric power."

a rotary contact-maker was used, and then the circuit was closed for a small fraction of a revolution. For this reason a very sensitive galvanometer was necessary. The majority of the observations were taken when using a moving coil mirror galvanometer giving a deflection of 560 mm. for 1 micro-volt on a scale distant 110 cm. from the mirror.

The contact-maker was arranged as represented in Fig. 109. The arrangement consisted of a pair of insulated platinum-

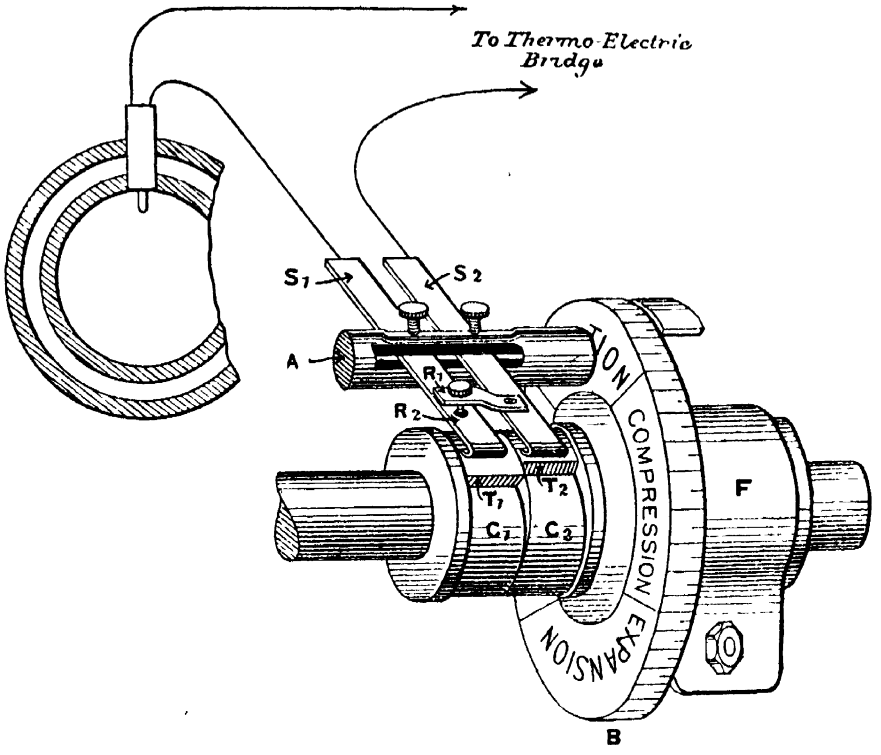


FIG 109.—Adjustable rotary contact-maker

pointed springs, S_1S_2, carried on the arm A of an adjustable wrist-plate B. The latter was secured in a friction grip F concentric with the lay shaft of the engine. A pair of cams, C_1C_2, rotated with the lay shaft to allow the platinum point R_1 of one spring to make contact with a platinum face R_2 on the other spring for an interval depending on the angular distance between the two steps T_1T_2—usually about 6°. For a complete cycle of readings the wrist-plate could be set in successive positions for the springs to make contact as the lay shaft

revolved. As the readings for a complete cycle took some time, every precaution had to be taken in such experiments to keep the running conditions of the engine as constant as possible.

The objections sometimes urged against this type of contact-maker are associated with the possible creation of electrostatic potentials by the frictional action between the springs S_1S_2 and the cams C_1C_2, and with the angular change required to make and break the contacts.

The results of Messrs. Coker and Scoble's measurements of wall temperatures may be briefly summarised as follows: The surface of the combustion chamber rose to about 250° C. (482° F.) in one place where the water cooling was least effective, with a cyclical change of about 20° C. (36° F.). The maximum temperature of the inlet valve was in the neighbourhood of 310° C. (590° F.) and had a cyclical change at the surface of 10° C. to 20° C.; at the exhaust valve the corresponding temperature was 400° C. (752° F.) with a cyclical change of 10° C. to 15° C. The piston of 7 in. diameter had a maximum temperature of about 340° C. (644° F.), with a considerable cyclical change at the centre of about 80° C. (144° F.) as a maximum value. The measurements of the gas temperatures in the cylinder are described later on p. 238.

In these tests the hot thermojunctions were formed by riveting thin iron wire into the bottom of cast-iron plugs where the metal was 0·02 in. thick, and apparently it was assumed that this gave the true temperature fluctuation at this depth in the body of the piston and of the valves. If the cyclical fluctuations of temperature were assumed to be sinusoidal, and the gradient of temperature induced by the cooling action of the jacket water were neglected, the laws of conduction suggest that the amount of heat flowing into the metal at the hot surface during the period of reception may be expressed by $\frac{4a}{\sqrt{N}}$ heat units per sq. ft. per cycle, where a is one-half the fluctuation of temperature and N is the number of cycles per minute. Although simple sinusoidal variations of temperature may not quite represent the conditions in this case it is well known that a periodic variation

may be usually expressed as a Fourier series of superposed sinusoidal variations. It will therefore be assumed that the above expression will serve for the present purpose, and for N equal to 120 cycles per minute the heat entering would be $0{\cdot}364 \times a$ per cycle per sq. ft. By similar calculations the amount of heat passing through the body of the metal at 0·02 in. depth in the same period of time would be about $0{\cdot}24 \times a$. If the conduction of heat along the thin wire of the junction were neglected as well as that which may flow edgeways into the body of the metal, all the heat $(0{\cdot}364 \times a)$ entering the metal at the junction would be stored in the metal of thickness 0·02 in. The rise of temperature during the reception of heat would be proportional to the amount of heat stored, therefore,

$$\frac{\text{Heat stored in 0·02 in. in wall}}{\text{Heat stored in 0·02 in. at couple}} = \frac{\text{Actual range of wall}}{\text{Range of thermocouple wall}}$$

$$= \frac{0{\cdot}364 - 0{\cdot}24}{0{\cdot}364} = \tfrac{1}{3} \text{ nearly.}$$

This result indicates that the ranges in the fluctuation of temperature of the metal as measured in these tests were possibly too large when compared with the conditions at the normal thickness of the metal, and the discrepancy represented by the above calculation is so large that the assumptions made could hardly modify this conclusion materially. It would seem to be necessary, therefore, when measuring temperature fluctuations, to use a wire of diameter comparable with the size of the bottom of the hole and in true metallic contact with the base. Riveting the wire into a small hole in the metal may not give, or may not retain, true metallic contact at the base.

In a course of four lectures * arranged by the University of London, Professor Dr-Ing. A. Nägel gave details of thermo-junctions he had used to measure the temperatures and temperature fluctuations in the cylinder walls and piston of a horizontal central exhaust or uniflow steam engine. Radial holes 15 mm. diameter were drilled at seven places in the cylinder walls. Plugs of cast-iron in two parts were ground

* "The Transfer of Heat in Reciprocating Engines," *Engineering*, Vol. CXXVII, 1929.

into these holes. Two holes 2 mm. diameter and 6 mm. apart were drilled in each plug to within 0·5 mm. of the inner surface, with the bottom of each hole hemispherical. Through the remaining thickness a 0·5 mm. hole was bored in the centre and in one hole a copper wire was fixed by riveting, and in the other a constantan wire was similarly fixed. These wires were insulated in the 2 mm. holes by glass beads and outside these holes by glass or rubber tubes. Although this arrangement was an improvement on previous thermojunctions the lecturer evidently recognised that possibly further improvements could be made, as is shown by the following quotation: "It must be confessed that the plug as described will not, in that form, record the temperature range of the inner part of the cylinder wall without any alteration. In making new tests the separate plate might be avoided and perhaps the holes might be made directly in the cylinder walls, in order to obviate the variable contact resistance of the ground surface. Possibly the holes could also be made less than 2 mm. diameter, and the wires insulated with very thin quartz tubing, or even only by lacquer that would stand up under high temperatures, such as is used in electro-technical work. . . ." A similar thermojunction was placed in the piston with the wires carried in glass tubes inserted into steel tubes and bent with them while hot to follow the shape of the piston, and then led outwards through an auxiliary piston rod, with porcelain insulation, made steam-tight and electrically insulated. The conductor wires were then bound together and to a steel wire hung from a spiral spring attached to a point in the ceiling.

Electrical resistance thermometers of tungsten wire were also inserted in the steam space in the cylinder to measure steam temperatures. In the first tests with these resistance thermometers the e.m.f. which caused a load current of 0·001 amp. across the ends of the tungsten wires fluctuated so much that the values could not be measured. This was ascribed to the porcelain rod insulators projecting into the steam space becoming electrically charged due to the frictional effect of the whirling steam. This difficulty was removed by gilding the outside of the porcelain rods close to the edges of the holes.

Rubbing contacts in the thermojunction and resistance thermometer circuits were avoided by using the Einthoven string type of galvanometer to indicate the voltages or currents on which the temperature measurements were based by previous calibrations. The galvanometer had a gold or a platinum thread stretched between the poles of an electromagnet excited by a constant current. One of the holes bored through the centre of the magnet poles accommodated a projecting microscope which magnified the central part of the thread 1000 times. Through the central hole in the other pole a beam of light, after passing through a condenser lens and a water vessel, was concentrated into a cone of light of highest intensity within which fell the middle part of the thread. The microscope gave a circular spot of light on a screen about half a metre distant in which the shadow of the thread was seen as a vertical line 6 mm. wide for the gold thread of 0·006 mm. diameter or 2 mm. wide for the platinum wire 0·002 mm. diameter. The electrical resistance of the gold thread was about 150 ohms and of the platinum thread about 3500 ohms. The beam of light passed through a horizontal slit about 0·2 mm. wide and a moving drum of photographic paper showed after development the shadow of the thread. A wooden disc attached to the crank-shaft had contacts corresponding to definite crank positions and discharged an electrically charged condenser across the primary circuit of an induction coil, which produced a spark in the secondary, photographed as a point of light on the paper. Selected temperature records were given in the lectures as well as an analytical treatment of the results obtained, including the influence of the passage of the piston rings over the surfaces of the cylinder. Consideration was also given to similar tests made on certain internal combustion engines using similar thermojunctions.

Some particulars of tests on an experimental Sulzer oil engine have been given by Mr. R. Sulzer.* The single cylinder engine operated on the two-stroke cycle, with the solid injection valve in the centre of the cylinder cover. The cylinder diameter

* " Recent Measurements on Diesel Engines and their Effect on Design," *Koninklijk Instituut van Ingenieurs*, Rotterdam ; or *The Engineer*, March 31, 1939.

was 720 mm. (28·34 in.) and the stroke 1250 mm. (49·22 in.), with normal full load speed of 120 r.p.m. Temperatures were measured at 28 points in the cover, liner, and oil-cooled piston by means of thermojunctions similar to those described above. The temperature of the piston was highest at the edge, about 500° C. (932° F.) at full load.

The work done in the cutting of metals in machine tools nearly all appears as heat energy and an important part of

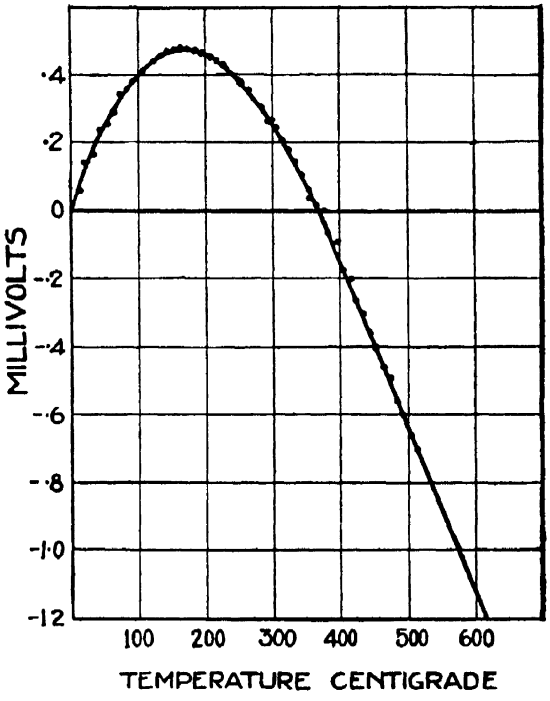


FIG. 110.—Calibration curve of No 1 stellite and steel couple

this energy is generated at or near the tool point. Attempts have been made to measure the temperature of the point by means of a thermojunction, but this may indicate an average result only. Mr. E. G. Herbert * made the cutting tool and the metal being cut into a thermocouple by insulating the tool and measuring the resulting e.m.f. For this purpose two stellite tools were used in a lathe; grade No. 1, used for light cuts, was harder and more brittle than No. 2 grade used

* "The Measurement of Cutting Temperatures," *Proc. Inst. Mech. Engs.*, No. 2, 1926, p. 289.

for the heavy cuts. For calibration the tool and a piece of the work material were either clamped or welded together and placed in an electric furnace with a standardised iron-constantan thermocouple connected to an indicator. The calibration curves obtained are shown in Figs. 110 and 111. It is seen that the No. 1 grade of stellite gave a neutral point, $\frac{de}{dt}=0$, at about 170° C. (338° F.) and a reversal of polarity at about 370° C. (698° F.). Similar points were given by No. 2 stellite at about 260° C. (500° F.) and 600° C. (1112° F.) respectively. The tool action in a lathe is usually fairly continuous for a considerable period of time and the e.m.f. could be measured by millivoltmeter. Some of the results with the No. 2 stellite tool turning mild steel bar $2\frac{1}{8}$ in. diameter are shown in Figs. 112 and 113. The tool had a top rake of 27° and clearance 6°, giving a depth of cut of $\frac{3}{8}$ in. The temperatures above the cold junction at 20° C. is given in Fig. 112 at various cutting speeds, with the feed at 43 revolutions per inch of traverse. The results shown in Fig. 113 were obtained at the fixed speed of 58·5 ft. per minute and at different rates of feed. If oil was used as the cutting lubricant the galvanic effect was negligible, but with water it was necessary to cover the tool with tallow. In intermittent cutting operations it was necessary to obtain a record and for this purpose Mr. Herbert used an Einthoven string galvanometer where the thread or string was a fibre of glass 0·007 mm. diameter coated with silver to make it conductive. A cylindrical lens served to magnify and concentrate the image or shadow of the thread on a slit, together with inscribed lines on the lens, behind which a photographic plate was allowed to move at a predetermined rate. The arm of a metronome was arranged to obscure the beam of light at intervals of 1 or $\frac{1}{2}$ second. It is evident from Figs. 110 and 111 that the same voltage is given at two different temperatures. Where a moving record is obtained,

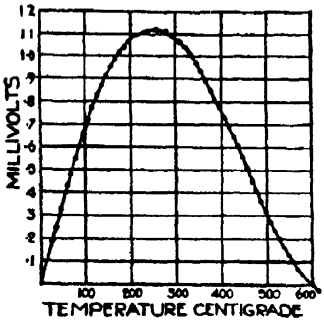


FIG. 111.—Calibration curve of No. 2 stellite and mild steel couple

however, usually there is not much difficulty in following the record.

Some further precautions may be needed when the action

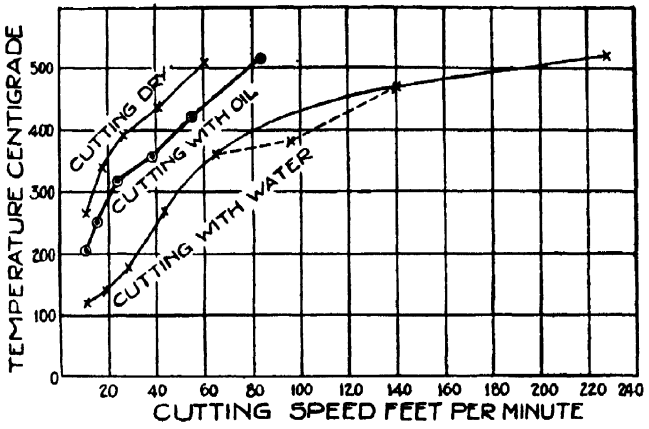


FIG. 112.—Speed and temperature on bar lathe.

is intermittent. For instance, photographic records from a hacksaw having a high-speed steel saw blade cutting mild steel bar indicated that the calibration should have a form

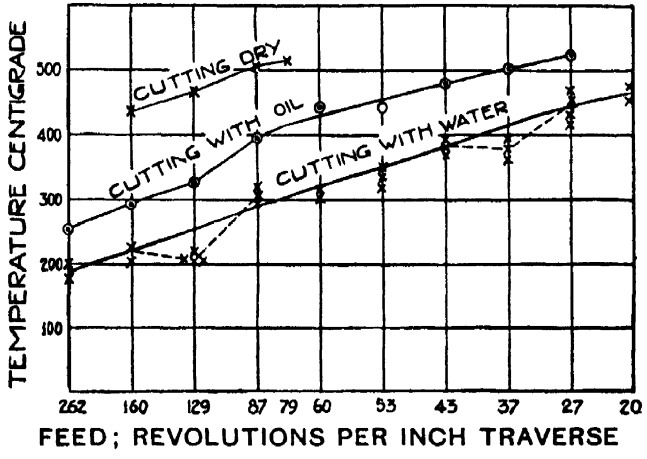


FIG. 113.—Feed and temperature on bar lathe.

similar to Figs. 110 and 111. The furnace calibration from 20° C. to 1125° C., however, showed an almost continuous rise of voltage with the temperature, with partial arrests at 600° C. and 900° C. Even when the couple was withdrawn from the furnace at each calibration temperature as soon as the reading

was steady the rise of voltage was still continuous, with a halt at about 730° C. These discrepancies were ascribed to the softening of the high-speed saw steel and the corresponding physical or chemical changes with heating in the calibration furnace, which may not occur when the heating and cooling occupy not more than a fraction of a second as in the operation of sawing at normal speeds. Apparently modern tool materials such as the cemented carbides can maintain a cutting edge up to about 1000° C. when making heavy cuts continuously at high speeds.

Similar methods * have been used experimentally to measure the flash of the rise of temperature at the momentary points or areas of contact between gear teeth when running at load.

When a motor vehicle or a railway train has to be slowed down or brought to rest quickly, the brakes are applied to the wheels and the kinetic energy stored in the moving masses, plus the gravitational work if on a declivity, less the work done against bearing friction or wind resistance, or perhaps in regenerative action, has to be dissipated by the frictional forces between the brake blocks and the brake wheels, and is there converted into heat. In general the frictional moment applied by the brake about the centre of a wheel should be less than the moment of sliding friction between the tyre and the road or rail, or the wheel may lock and thereby cause flats to be worn on the tyre. The conditions are particularly severe on railway trains, especially on heavy surburban services, and it is a common experience to see flying sparks coming from the brake blocks or tyres, which is some evidence of the localised nature of the contact, with the resulting high temperatures at some of the points of contact. The conditions are usually aggravated by the complicated and unequal relative expansion which may take place. Examination of the surface conditions in railway brake blocks operating under standard conditions indicates that the initial application of the brakes results in localised contact areas between the block and the

* "Measurement of Temperature Flashes on Gear Teeth under Extreme Pressure Conditions," by H. Blok, *General Discussion on Lubrication*, 1937, Vol. 2, p. 14, I.Mech.E.; "Theoretical Study of Temperature Rise at Surfaces of Actual Contact under Oiliness Lubricating Conditions," *ibid.*, p. 222.

tyre, largely confined to one or more thin strips along the length of the block. As these raised areas of the block wear away further areas come into contact with the result that the strip contact areas tend to move to and fro across the block.

Measurements of the surface temperatures of railway tyres made under experimental conditions by Messrs. R. C. Parker * and P. R. Marshall show that the temperatures of the raised areas of the tyre increase with the kinetic energy dissipated. Even for conditions which may be regarded as moderate in service, temperatures above 800° C. (1472° F.) were registered. The production of heat spots at this temperature on the tyre may ultimately cause the development of cracks and may initiate rapid wear of the blocks. Whatever method may be adopted to measure the temperature it should be capable of giving a very rapid response, since the spots of high temperature coming from under the brake block cool very rapidly. The above-mentioned experimenters decided to make use of the lead sulphide photo-conductive cell to receive the radiations from the tyre, following the suggested possibilities of this cell by Messrs. E. Lee † and R. C. Parker. The evaluation of the temperature of a surface from a measurement of the emitted radiation involves one of two methods. Either a simple calibration may be made whereby the effect of the radiation on the resistance of the cell is measured when the surface is held at known temperatures, or else the radiation from a black body may be measured over a suitable temperature range and a subsidiary measurement made of the surface emissivity of the material of the tyre. The experimenters preferred the latter method.

The effective response of the lead sulphide cell evidently begins at the radiation wave-length of about 3·6 microns ($3{\cdot}6 \times 0{\cdot}001$ mm.) and reaches a maximum at about 2·6 microns, and then falls off more gradually as the wave-length decreases further. The equation 10 on p. 96, based on Wien's law, was used to define the emissivity E_0, with an average value

* " The Measurement of the Temperature of Sliding Surfaces, with Particular Reference to Railway Brake Blocks," *Proc. Inst. Mech. Engs.*, 1948, Vol. 158, No. 2, p. 209.

† " Use of Lead Sulphide Photo-Conductive Cells for High-speed Pyrometry," *Nature*, 1946, Vol. 158, p. 518.

λ_a in microns to express the wave-length of the radiations. Thus, as used

$$\log_{10} E_0 = \log_{10} \frac{I_1}{I} = \frac{6220}{\lambda_a} \times \left(\frac{1}{T} - \frac{1}{T_1} \right),$$

where T is the absolute temperature at which the intensity of the emitted radiation equals that from a "black" body at the absolute temperature T_1 °C.

A block diagram of the calibration apparatus used is given in Fig. 114. A sample of the tyre steel in the form of a small

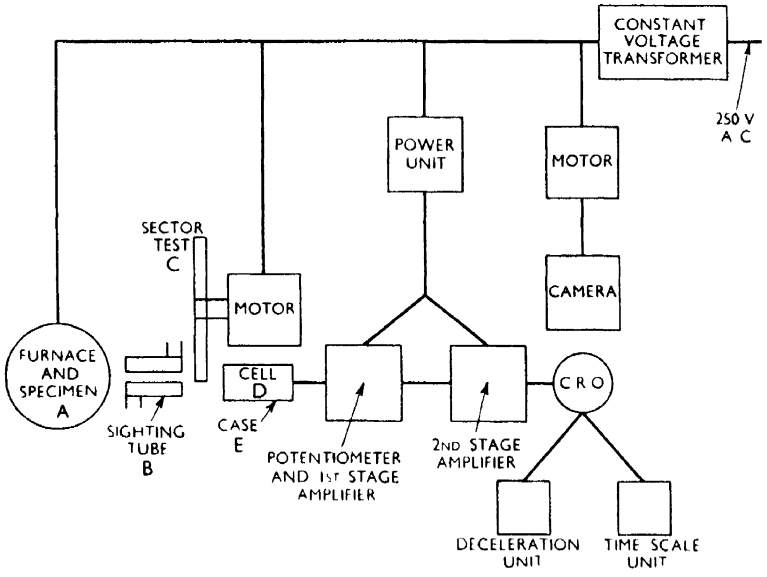


FIG. 114.—Block diagram of experimental layout.

hollow cylinder was arranged opposite the window of a vacuum furnace A. The window was made of glass from a thin microscope cover slide having a transmission coefficient of 92%. The high vacuum in the furnace was required to prevent the oxidation of the bright steel and to avoid loss of heat from the surface of the specimen by conduction and convection. The radiation from the specimen passed through a copper sighting tube B of 0·25 in. diameter. This tube was water-cooled and the internal surface was grooved and coated with carbon black to reduce internal reflections to a minimum. The radiation leaving this tube was interrupted or chopped 1020 times per second by means of the sectored disk C running

at constant speed, and then fell on to the cell D placed inside the earthed metal case E, passing through an aperture 15 mm. long and 4 mm. wide in the front face of the case arranged parallel to the sensitive elements of the cell. A predetermined external potential was maintained across the cell by means of an external potentiometer, using accumulators as a source of power. The output from the cell was fed through a tuned anode frequency selective amplifier to a two-stage resistance capacity coupled amplifier, the output of which was taken to the Y_1 plate of a "Cossor" double-beam cathode ray oscillograph. The cell had a response time of 0·1 millisecond, but in order to obtain the required sensitivity the band width of the amplifier had to be adjusted to give an overall response time of 1 millisecond. The hot junction of a platinum-platinum, rhodium thermocouple was placed in contact with the inner surface of the hollow specimen cylinder to measure the actual temperature of the steel specimen. The furnace had a water-cooled jacket provided mainly to ensure that the only radiation entering the sighting tube was that from the specimen. By this means the relation between the temperature of the specimen and the deflection δ of the cathode ray oscillograph were related by following the Wien law and the relationship between the intensity of radiation I and the deflection δ expressed by,

$$\log_{10}\frac{\delta_1}{\delta_2}=\frac{6220}{b\lambda_a}\left(\frac{1}{T_2}-\frac{1}{T_1}\right).$$

In order to connect this law with the absolute temperatures T_1 and T_2 in deg. Cent. the values of b and λ_a would need to be determined.

To evaluate b the deflection δ was noted for different values of the incident radiation obtained by altering the distance d between the cell and a furnace kept at a constant temperature. The intensity should vary inversely as d^2 and the plot of δ against $\frac{1}{d^2}$ gave a value for $b=1{\cdot}38$ in this combination.

To test the validity of the Wien equation in this relation a series of readings were taken in the vacuum furnace for the tyre steel specimen over the temperature range 550–900° C. (1022–1652° F.). Readings were first obtained with the absolute pressure in the furnace of $5{\cdot}6\times10^{-5}$ mm. mercury,

at which low pressure the steel remained bright, and were repeated after the steel had received a coating of oxide by exposure in the furnace at a higher pressure. A plot of $\log_{10}\delta$ against the reciprocal of the absolute temperature gave $\lambda_a = 1{\cdot}99$ and $1{\cdot}98$ respectively. To obtain the emissivity E_0 it remained to replace the vacuum furnace with a "black" body radiator and to measure values of δ at a range of temperature lower than previously used depending upon the value of E_0. The results obtained gave $\lambda_a = 1{\cdot}97$. Substituting these values of b and λ_a gave an emissivity value E_0 of $0{\cdot}27$ for bright steel and $0{\cdot}32$ for the oxidised steel.

The actual brake tests were carried out with standard materials. The testing machine comprised a 100 h.p. motor, two banks of flywheels, a railway wheel complete with tyre all mounted on a shaft, and an articulated torque-arm arrangement carrying two brake blocks. The pressure applied to the blocks was obtained from an oil cylinder which, in turn, derived its pressure from weights placed on an oil ram. The torque arm was pivoted about the axis of the shaft and was free to turn against oil cylinders connected to hydraulic recording gauges. The speed of rotation ranged from zero to 1000 r.p.m.

The surface temperature of the tyre as it came from under the brake block was measured by directing the sighting tube normally on to the surface with the nose of the tube placed sufficiently close to the tyre to prevent hot wear products being blown across its opening. The sighting tube and the cell were fixed to an adjustable mount which enabled the tube and cell to be traversed across the width of the tyre. The radiation path used in the calibrations was matched by fitting a longer nosepiece to the sighting tube and placing a piece of microscope cover slide glass over the cell aperture. At a speed of 60 miles per hour only $0{\cdot}2$ millisecond interval elapsed between the point of the tyre leaving the edge of the block and crossing the tube.

In order to obtain a permanent record from the cathode ray oscillograph a camera was attached and fitted with a drive which gave a film speed of 40 cm. per second. The film was marked with the tyre positions by having a disk with fifteen holes equally spaced and driven by a chain from the shaft carrying the railway wheel. A beam of light which

was directed through this disk on to a photo-cell amplifier unit was thus interrupted 15 times per second and this was connected to the Y_2 plate or beam of the cathode ray oscillograph. A time scale was given on the film by interrupting a second beam of light by means of a rod rotated about its centre at a constant speed.

Tests were made with different circumferential lengths of brake block and the results indicated that blocks shorter than the standard length would be equally effective at lower cost and would almost eliminate the localised high temperatures mentioned on p. 231 which was such a feature of the results with the standard length of block.

Various attempts have been made to measure the temperature of the gases in a gas engine cylinder at different points in the cycle both by means of platinum resistance thermometers and by thermojunctions. The greatest difficulty has been experienced in keeping the platinum wires intact for the reasons that the highest temperature after a normal explosion is generally beyond the melting point of platinum, and thin wires are liable to breakage on account of the intense convection currents in the gases. By using relatively thick platinum wires, 0·0015 to 0·0025 in. diameter, Professor Burstall * found that it was possible to preserve the platinum wire against fusion in a small gas engine using coal gas, provided only weak charges were used with about one explosion in six cycles, but no doubt this was only in consequence of the appreciable lag of temperature involved by the use of such relatively thick wires. Attempts made with platinum wires 0·001 in. diameter failed because the wire always fused after a very few explosions.

Professors Callendar and Dalby † experimented on the measurement of gas temperatures on a small gas engine. They used a platinum resistance wire of 0·001 in. diameter and found that the lag of temperature with such a fine wire was quite small, but they attached this thermometer to a special valve in the centre of the admission valve and operated by a special cam on the side shaft. The spindle of the special

* " Second Report to the Gas-Engine Research Committee," *Proc. Inst Mech. Engs.*, 1901, p. 1031.

† *Proc. Roy. Soc.*, Vol. LXXX, 1908, p. 57.

thermometer valve near the head was formed of two ribs made as thin as possible so as to leave the contained platinum wire freely exposed to the gases when the valve was open. It was arranged that the thermometer valve should be open during the suction and compression strokes only and remain on its seat on the admission valve during the high temperature period of the cycle. By this means the gases at high temperatures were kept out of contact with the platinum wire. A special contact-maker was employed similar to that illustrated in Fig. 109 on p. 222 so as to obtain the temperature of the gas at any point of the cycle when the thermometer valve was open.

The average temperatures of the gases during expansion were calculated by means of the gas formula $\frac{PV}{T}$=constant, after allowance for the shrinkage of volume due to chemical combination. This involved the accurate measurement of the absolute pressure P and volume V at all points in the cycle. For this purpose the manograph type of optical indicator was used having a pressure diaphragm operating a tilting mirror, by which means a beam of light was thrown on to a sensitized plate and gave a record of pressures at all points in the cycle. The reason for using such an indicator is the lack of accuracy of ordinary piston and pencil indicators due to the inertia and the frictional resistance of the moving parts.

Thus in this case, if P_1, V_1 and T_1 represent the absolute pressure, absolute volume and absolute temperature respectively at a particular point during compression, and P_2, V_2 and T_2 represent the corresponding values at any particular point on the subsequent expansion stroke, with 2·2% allowed for shrinkage of volume by the combustion, then,

$$\frac{P_1V_1}{T_1}=\frac{P_2}{T_2}V_2\left(\frac{100}{100-2\cdot2}\right).$$

Since all the values are known except T_2, then,

$$T_2=\frac{P_2}{P_1}\times\frac{V_2}{V_1}\times T_1\times 1\cdot022.$$

In the above calculation it is assumed that the combustion is complete and that there is no appreciable leakage of gases from the cylinder between the points considered. Therefore, care should be taken to have the valves and piston rings in

good condition during the experiments. Similar estimates for T_2 in Diesel or compression-ignition engines would need to take into account the added weight of the injected fuel oil on the expansion stroke.

It is to be noted, however, that the calculated temperatures are averages for the gases at any particular instant during expansion. The late Professor Hopkinson * made some experiments with a large cylindrical explosion vessel of capacity 6·2 cu. ft., in which he measured the temperatures of the gases at different points in the vessel after the explosion, also measuring the pressure by means of an optical indicator. Each thermometer consisted of a coil of about 5 cm. of pure platinum wire 0·001 in. diameter. The leads were of copper carried in glass tubes to protect them from the action of the flame. Each thermometer coil was placed in series with a storage cell and with a moving coil galvanometer having a comparatively stiff phosphor-bronze suspension. The natural period of oscillation was thus made from $\frac{1}{50}$ to $\frac{1}{30}$ second, with the result that the oscillations were sufficiently small and rapid to cause little trouble in getting a mean reading of the variation of current in the platinum coil due to alteration of resistance with temperature. The mirror of the galvanometer was arranged to throw the image of a fine hole, illuminated by an arc lamp, on to a revolving drum carrying a photographic film. The record of pressures was also taken on the same drum.

It was always found that the temperature near the point of ignition (at centre of vessel) at the moment of maximum pressure was always higher than at other places in the vessel. With a mixture of 1 volume of coal gas to 9 volumes of air ignited at atmospheric pressure, Professor Hopkinson estimated the following distribution of temperatures at the point of maximum pressure when the gas was ignited at the centre of the vessel.

Time to attain maximum pressure after ignition, about	0·25 sec.
Temperature at centre of vessel	1900° C.
,, ,, 4 in. from wall	1700° C.
,, ,, 0·4 in. from wall at end	1100–1300° C.
,, ,, 0·4 in. from wall at side . .	850° C.
Mean temperature (estimated from pressure) .	1600° C.

* *Proc. Roy. Soc.*, 1906.

Within half a second after the maximum pressure was attained convection had time to take effect and the distribution of temperature was much more uniform as is shown by the following values.

Time from ignition	0·75 sec.
Temperature at centre of vessel . . .	1100–1200° C.
Mean temperature determined by a long platinum wire from centre to near the wall (excluding layer of gas 1 cm. thick near wall) . .	1160° C.
Mean temperature (estimated from pressure) .	1100° C.

In a gas engine cylinder, however, convection is much more intense than in a gas vessel of constant volume used in the manner described, for the reason that the gases are in very rapid motion both just before and after entering the engine cylinder, and it is well known that the rapidity of combustion is much greater in a gas engine cylinder than in a gas vessel of constant volume, due to these intense convection currents.

In the course of the experiments discussed previously on pp. 219 to 224, Messrs. Coker and Scoble made a fairly successful attempt to measure directly the cyclical temperatures of the gases, near the top of the combustion chamber. They used a thermojunction with one wire an alloy of platinum and rhodium 10%, and the other an alloy of platinum and iridium 10%, both wires being obtained from Messrs. Johnson, Matthey and Co. It was found that these alloys were able to withstand the temperature of the explosion under normal conditions with an explosion every cycle when the thin wires were flattened to a thickness of $\frac{5}{10,000}$ to $\frac{8}{10,000}$ inch. The couple was arranged as shown in Fig. 115, where the steel sheath D was pressed against a seating at V in the special casting at the top of the combustion chamber. A two-way fire-clay tube A containing the couple was secured in the sheath with plaster of Paris. The inner ends of the wires were rolled out to the required thickness and fused together electrically, and afterwards the junction was finally rolled out to the thickness mentioned above. The strip so formed was trimmed down to approximately the contour of two truncated triangles with the central junction at the narrowest part. This form was adopted to provide a loop strong enough to hang in a vertical

position in spite of the violence of the explosions, and it was therefore set with the planes of its flat faces parallel to the axis of the engine cylinder to offer the smallest obstruction, and was arranged to project about ½ in. into the cylinder. When examined through a magnifying glass the edges of the wires sometimes showed signs of fusion and consequent thickening after long exposure. With an abnormal explosion the wires were generally fused at the junction.

In order to test the delicacy of the indications of these couples at low temperatures a number of experiments were made with the exhaust valve locked and the engine motored

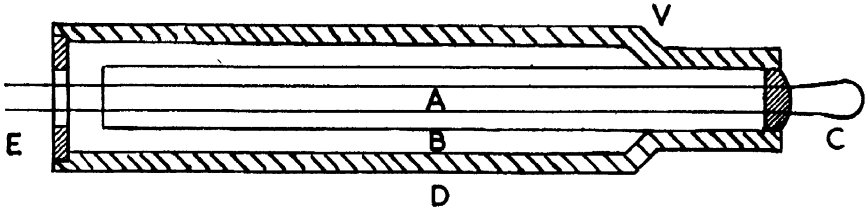


FIG 115.—Arrangement of thermojunction for measuring gas temperatures in gas engine cylinder

round, and a very fair agreement was obtained between the temperatures calculated from the compression and expansion of the trapped air and those observed with the thermocouples. The e.m.f. obtained at the highest temperatures of explosion varied between 7 and 8 millivolts. Calibrations were checked by Dr. Harker at the National Physical Laboratory up to 1283° C. (2341° F.), as shown in the following table.

Temperature, ° C. $=t$.	0	490	840	1003	1283
Electromotive force, microvolts $=e$ . .	0	3152	5036	5773	6382

These results correspond fairly well with the formula:

$$e = -174 + 7{\cdot}6075t - 0{\cdot}001673t^2,$$

and this expression was used to determine the temperatures obtained in the trials on the assumption that it held for extrapolated values beyond the range of calibration.*

Two of the curves of the temperature cycle of the gas

charge are shown in Fig. 116. The maximum temperature here recorded is 1675° C., which, allowing for the cold junction correction to 0° C., gave a maximum temperature of 1705° C. In this case a further estimate of the highest temperature was obtained, for it was found that the e.m.f. of the couple suddenly became lower at the explosion point, although at other points it remained much the same, as shown by the dotted curve. On taking out the couple it was found that this was due to the junction fusing without breaking. Some tests

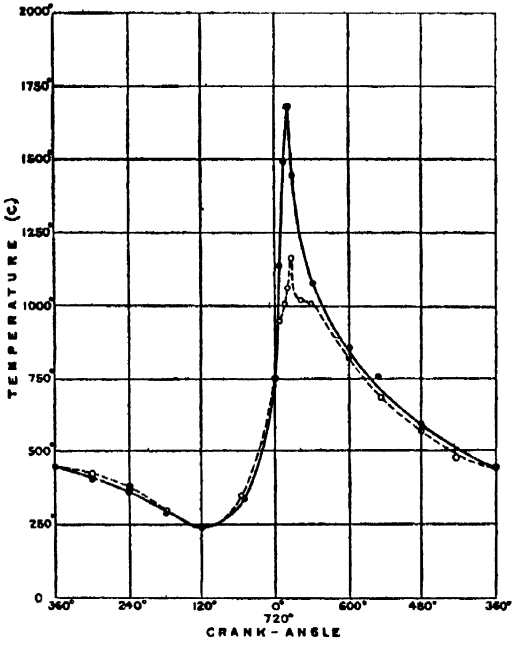


FIG. 116.—Measured temperatures of gases in a gas engine.

made by Dr. Harker at the National Physical Laboratory on these 10% alloys showed that they both melted at a temperature about 100° C. higher than the melting point of platinum, that is, at about 1850° C. (3362° F.) and therefore this temperature must have been attained by the fused couple.

Some further experiments were made with the addition of an optical indicator to measure the highest pressures obtained during the explosion. The pressures, volumes and temperatures were measured at points on the compression and expansion curves to obtain the value of the gas constant, $\frac{PV}{T}$, and

from this to calculate the average temperature corresponding to the maximum pressure. The maximum average temperature was estimated to be about 1870° C.

There is always some uncertainty with these couples because platinum-iridium alloy changes with prolonged heating at high temperatures, with a consequent influence on the electromotive force. Considering this influence, the experimenters concluded that the decline of the e.m.f. during an ordinary trial would be less than $2\frac{1}{2}\%$. There is also some danger of the wires becoming contaminated from the gases at high temperatures.

A thermocouple was inserted in the centre of the exhaust pipe as near to the cylinder outlet as possible. The couple was pure platinum and a 10% alloy of iridium-platinum. The result of all the variations in the conditions of running of this engine was to produce a difference of about 40° C. in the maximum temperature of the gases in the exhaust pipe, which always lay between 500° C. (932° F.) and 550° C. (1022° F.).

In all these experiments no account appears to have been taken of the radiation from the surface of the wires forming the thermocouple in the combustion chamber. It is generally accepted that, within limits, the total radiation from platinum is proportional to the fifth power of the absolute temperature. Thus at high temperatures the thermocouple would be a fairly effective radiator to the comparatively cold walls of the combustion chamber. Probably the presence of the surrounding gases would interfere little with the rate of heat loss by radiation, and it may be suggested that, due to radiation, there is the possibility of appreciable errors in the measurement of the gas temperature during the high temperature period of the cycle. In other words, when the wire is losing heat by radiation its temperature tends to fall, and at any instant its temperature would be as much below that of the gas as would be required for the heat lost by radiation to be made up by heat received by radiation and by contact with the gases.

To illustrate this particular point the late Professor Callendar made experiments * on two platinum wires as resistance ther-

* Discussion on " Second Report to the Gas-Engine Research Committee," *Proc. Inst. Mech. Engs.*, 1901, p. 1111.

mometers, one being $\frac{6}{1000}$ in. diameter and the other $\frac{4}{1000}$ in., first placed together in a porcelain tube and connected differentially with a recording instrument. When the two wires were heated together in the porcelain tube the indication of the apparatus did not vary, showing that they were at the same temperature ; but when directly exposed to the flame, the finer wire became about 60° C. hotter than the other. Dr. F. Haber * estimated that a thermojunction with wires about 0·1 mm. (0·004 in.) diameter and exposed to a Bunsen flame has a temperature more than 30° C. below the true temperature of the flame. Although the influence of radiation from a round wire as small as 0·001 in. diameter is likely to be relatively small the wires of the thermojunction used by Messrs. Coker and Scoble were flattened and thus probably had a relatively large radiating surface. The influence of this cannot be estimated without further experiments.

The estimated gas temperature T_2 based on the equation on p. 236 not only depends on the accurate measurement of a temperature T_1 but also on the ratios $\frac{V_2}{V_1}$ and $\frac{P_2}{P_1}$. Usually the former ratio is readily obtainable for selected points, but the latter ratio is much more difficult to measure accurately, especially in high-speed internal combustion engines. Indicators have been designed having a diaphragm instead of a piston and spring, with optical mirror reflection in place of multiplying linkwork. In later designs there was a definite return to the piston type. Another modification was developed by the R.A.E., now made as the " Farnboro " indicator by Dobbie McInnes, Ltd. In recent years the cathode ray oscillograph engine indicator has been introduced. The problems associated with this type of indicator have been discussed in practical terms.† One of the main difficulties concerns the reliable translation of rapidly varying high pressures into electrical or magnetic impulses.

* *Thermodynamics of Technical Gas Reactions.*

† " The Admiralty Cathode Ray Oscillograph Engine Indicator," by Smith, Lakey, and Morgan, *Proc. Inst. Mech. Engs.*, 1940, Vol. 143, No. 1, p. 39 ; " Basic Principles in the Design of Cathode Ray Oscillograph Engine Indicators," by F. D. Smith, *ibid.*, p. 48 ; " Discussion on above papers," *ibid.*, No. 4, p. 279.

APPENDIX I*

THE INTERNATIONAL TEMPERATURE SCALE OF 1948

PART I

INTRODUCTION

THE Kelvin scale, on which temperatures are designated as ° K. and denoted by the symbol T, is recognised as the fundamental thermodynamic scale to which all temperature measurements should ultimately be referable. On this scale the interval between the ice point, T_0, and the steam point, T_{100}, is 100 degrees. The Kelvin scale and the thermodynamic Celsius scale, on which the temperature is $T-T_0$, are hereby adopted, in principle, by the Ninth General Conference of Weights and Measures.† Any temperature interval expressed on one of these scales will have the same numerical value as when expressed on the other.

PART II

DEFINITION OF THE INTERNATIONAL TEMPERATURE SCALE OF 1948

Temperatures on the International Temperature Scale of 1948 will be designated as " ° C." or " ° C. (Int. 1948) " and denoted by the symbol t.

The means available for interpolation lead to a division of the scale into four parts.

(*a*) From 0° C. to the freezing point of antimony the temperature t is defined by the formula

$$R_t = R_0(1 + At + Bt^2)$$

where R_t is the resistance, at temperature t, of the platinum wire between the branch points formed by the junctions of the current

* From data supplied by the *National Physical Laboratory*, Teddington, Middlesex.

† The General Conference, which was held in October, 1948, decided to discontinue the use of the words " centigrade " and " centesimale " and to replace them by " Celsius."

and potential leads of a standard resistance thermometer. The constant R_0 is the resistance at 0° C., and the constants A and B are to be determined from measured values of R_t at the boiling point of water and sulphur. The platinum in a standard resistance

TABLE I

Fundamental fixed points and primary fixed points under the standard pressure of 1 013 250 dynes/cm.² *	Temperature of equilibrium ° C.
Liquid oxygen and its vapour (boiling point of oxygen)	−182·970
Ice, and air saturated water (melting point of ice). (Fundamental fixed point)	0
Liquid water and its vapour (boiling point of water). (Fundamental fixed point)	100
Liquid sulphur and its vapour (boiling point of sulphur)	444·600
Solid and liquid silver (freezing point of silver) .	960·8
Solid and liquid gold (freezing point of gold) .	1063·0

thermometer shall be annealed and of such purity that R_{100}/R_0 is greater than 1·3910.

(*b*) From the boiling point of oxygen to 0° C., the temperature t is defined by the formula

$$R_t = R_0[1 + At + Bt^2 + C(t-100)t^3]$$

where R_t, R_0, A and B are determined in the same manner as in (*a*) above and the constant C is calculated from the measured value of R_t at the boiling point of oxygen.

(*c*) From the freezing point of antimony to the freezing point of gold the temperature t is defined by the formula

$$E = a + bt + ct^2$$

where E is the electromotive force of a standard thermocouple of platinum and rhodium-platinum alloy, when one junction is at 0° C. and the other is at the temperature t. The constants a, b, and c are to be calculated from measured values of E at the freezing points of antimony silver and gold. The antimony used in determining these constants shall be such that its freezing temperature, determined with a standard resistance thermometer, is not lower than 630·3° C. Alternatively, the thermocouple may be calibrated

* This corresponds to 760 m.m. high column of mercury having a density of 13·5951 g/cm.³ and subject to a gravitational attraction of 980·665 dynes/gram. $=p_0$.

by direct comparison with a standard resistance thermometer in a bath at any uniform temperature between 630·3 and 630·7° C.

The platinum wire of the standard thermocouple shall be annealed and of such purity that the ratio R_{100}/R_0 is greater than 1·3910. The alloy wire shall consist nominally of 90% platinum and 10% rhodium by weight. When one junction is at 0° C. and the other at the freezing point of antimony (630·5° C.), silver or gold, the completed thermocouple shall have electromotive forces, in microvolts, such that

$$E_{Au} = 10300 \pm 50\ \mu V.$$
$$E_{Au} - E_{Ag} = 1185 + 0{\cdot}158(E_{Au} - 10310) \pm 3\ \mu V.$$
$$E_{Au} - E_{Sb} = 4776 + 0{\cdot}631(E_{Au} - 10310) \pm 5\ \mu V.$$

(*d*) Above the gold point the temperature t is defined by the formula

$$\frac{J_t}{J_{Au}} = \frac{e^{\frac{C_2}{\lambda(t_{Au}+T_0)}} - 1}{e^{\frac{C_2}{\lambda(t+T_0)}} - 1}$$

in which

J_t and J_{Au} are the radiant energies per unit wave-length interval at wave-length λ, emitted per unit time by unit area of a black body at the temperature t and at the freezing point of gold, t_{Au}, respectively.

C_2 is 1·438 cm. degrees.

T_0 is the temperature of the ice point in ° K.

λ is a wave-length of the visible spectrum.

e is the base of Napierian logarithms.

PART III

RECOMMENDATIONS

Standard Resistance Thermometer.—A standard resistance thermometer should be so designed and constructed that the platinum resistance wire is as nearly strain-free as possible and will remain so in use. The most suitable platinum wire is that drawn from a fused ingot, not from forged sponge.

Satisfactory thermometers have been made with wire as small as 0·05 mm. and as large as 0·5 mm. in diameter, with a short portion of each lead adjacent to the resistor being made of platinum and continuing with gold wire through the region of temperature gradient. The completed resistor of the thermometer should be

annealed in air at a temperature not lower than about 450° C., or if it is to be used at temperatures above 450° C., at a temperature higher than the highest temperature at which it is to be used. It is recommended that the tube protecting the completed resistor be filled with gas containing some oxygen.

A useful criterion, which serves as a safeguard against inferior construction of the completed thermometer and against errors in the calibration at the fixed points is that $\frac{R_s - R_0}{R_{100} - R_0}$ (where R_s is the resistance at the boiling point of sulphur) should be between 4·2165 and 4·2180. Similarly, if the thermometer is calibrated for use in the range below 0° C., the ratio $\frac{R_s - R_{O_2}}{R_{100} - R_0}$ (where R_{O_2} is the resistance at the boiling point of oxygen) should be between 6·143 and 6·144. The constancy of resistance at a reference point, such as the triple point of water (or the ice point), before and after use at other temperatures, is also a valuable criterion of the adequacy of the annealing and the reliability of the thermometer in service.

Standard Thermocouple.—Satisfactory standard thermocouples have been made of wires not less than 0·35 mm. and not more than 0·65 mm. in diameter. Before calibration, the wires of the couple should be annealed in air for an hour at about 1100° C. The wire of the thermocouple should be mounted so as to avoid all mechanical constraints in the region where steep temperature gradients are likely to occur.

Zero Point of the Scale.—The temperature 0° C. may be realised experimentally well enough for nearly all purposes by the use of a mixture of finely divided ice and water saturated with air at 0° C. in a well-insulated container such as a Dewar flask. It is recommended, however, that for work of the highest precision the zero point be realised by means of the triple point of water, a point to which the temperature + 0·0100° C. has been assigned.

Realisation of the Triple Point of Water.—The temperature of equilibrium between ice, liquid water, and water vapour has been realised in glass cells from 4 to 7 cm. in diameter which have an axial re-entrant well for thermometers and contain only water of high purity. The amount of water should be such as to permit adequate immersion of the thermometer and to ensure the existence of the three phases during measurements. Such cells, when properly prepared for use and kept entirely immersed in an ordinary ice bath, have been found to be capable of maintaining a temperature constant to about 0·0001 degree for several days.

Realisation of the Melting Point of Ice.—By observing precautions concerning the purity of ice and water, the saturation of the water at 0° C. with uncontaminated air, and the effect of pressure, a temperature reproducible within a few ten-thousandths of a degree may be realised.

The effect of pressure may be calculated from the formula

$$t = 0{\cdot}0099\left(1 - \frac{p}{p_0}\right) - 0{\cdot}7 \times 10^{-6}H$$

where t is the equilibrium temperature, p is the prevailing atmospheric pressure at which the water is saturated with air, and H is the depth (in mm.) below the surface of the mixture of water and ice.

Boiling Point of Oxygen.—The temperature of equilibrium between liquid oxygen and its vapour is usually realised experimentally by the static method. The platinum resistor of the standard thermometer and the free surface of the liquid oxygen in its container are brought to the same temperature in a suitable cryostat, such as a metal block in a well-stirred bath of liquid oxygen. The tube, which connects the space containing the pure liquid oxygen to the manometer used for the measurement of the vapour pressure, should be protected against temperatures lower than the temperature of the pure liquid oxygen at the location of the resistor of the standard resistance thermometer.

The equilibrium temperature t_p, corresponding to a pressure p, may be found to an accuracy of a few thousandths of a degree, over the range from $p = 660$ to $p = 860$ mm., by means of the formula

$$t_p = -182{\cdot}970 + 9{\cdot}530\left(\frac{p}{p_0} - 1\right) - 3{\cdot}72\left(\frac{p}{p_0} - 1\right)^2 + 2{\cdot}2\left(\frac{p}{p_0} - 1\right)^3$$

or, to the same accuracy but over a wider range, by the formula

$$t_p = -182{\cdot}970 + \frac{21{\cdot}94 \log_{10} \dfrac{p}{p_0}}{1 - 0{\cdot}261 \log_{10} \dfrac{p}{p_0}}$$

Boiling Point of Water.—The temperature of equilibrium between liquid water and its vapour is realised by the dynamic method with the thermometer in the saturated vapour using apparatus of various designs, some closed and others open to the atmosphere. Closed systems, in which a boiling-point apparatus and manometer are connected to a manostat of large volume filled with helium, are preferable for precise calibrations at the boiling point of water.

The design of the boiling-point apparatus should be such as to

avoid any superheating of the water vapour around the thermometer, contamination with air or other impurities, and radiation effects. A criterion that the equilibrium temperature has been attained is that the observed temperatures corrected to a constant pressure should be independent of elapsed time, of variations in the heat supply to the liquid, of variations in the heat loss from the walls, and of the depth of immersion of the thermometer.

The equilibrium temperature t_p, corresponding to a pressure p, may be found to an accuracy within 0·001 degree over the range from p=660 to p=860 mm. by means of the formula

$$t_p = 100 + 28{\cdot}012\left(\frac{p}{p_0} - 1\right) - 11{\cdot}64\left(\frac{p}{p_0} - 1\right)^2 + 7{\cdot}1\left(\frac{p}{p_0} - 1\right)^3$$

or, to the same accuracy over a wider range, by the formula

$$t_p = 100 + \frac{64{\cdot}500 \log_{10} \frac{p}{p_0}}{1 - 0{\cdot}1979 \log_{10} \frac{p}{p_0}}.$$

Boiling Point of Sulphur.—The sulphur used in a sulphur boiling-point apparatus should not contain more than 0·005% of impurities. Selenium and arsenic are the impurities which have been found most likely to be present in quantities sufficient to effect the temperature of equilibrium to a significant extent.

In the usual type of sulphur boiling-point apparatus which has proved to be satisfactory for an accuracy of 0·01 to 0·02 degree, the sulphur is contained in a tube of glass, fused silica, or similar material with an internal diameter of 4 to 5 cm. The length of the tube is determined by the consideration that the vapour column must be long enough to accommodate a radiation shield and to permit the necessary depth of immersion of the resistance thermometer. Electric heating is preferable. Above the source of heat the tube is surrounded by heat-insulating material.

In a recent work in which an accuracy of about 0·001 degree was desired, the thermometer was not immersed directly in the sulphur vapour, but in an aluminium thermometer well, thus adapting the apparatus for use with a closed system. The thermometer well is provided with one or more radiation shields so designed that the interior of the shield approximates to a black body but with ample openings for circulation of sulphur vapour throughout the interior. An electric heater is provided to control the heat loss from the walls.

A criterion that equilibrium temperatures have been attained is that the observed temperatures corrected to a constant pressure should be independent of elapsed time, of variations in the heat supply to the liquid, of variations in the heat loss from the walls, and of the depth of immersion of the thermometer.

The equilibrium temperature t_p, corresponding to a pressure p, may be found to an accuracy of about 0·001 degree over the range from p=660 to p=800 mm., by means of the formula

$$t_p = 444{\cdot}6 + 69{\cdot}010\left(\frac{p}{p_0} - 1\right) - 27{\cdot}48\left(\frac{p}{p_0} - 1\right)^2 + 19{\cdot}14\left(\frac{p}{p_0} - 1\right)^3$$

or, over a wider range by the formula

$$t_p = 444{\cdot}6 + \frac{158{\cdot}92 \log_{10} \frac{p}{p_0}}{1 - 0{\cdot}234 \log_{10} \frac{p}{p_0}}.$$

Freezing Points of Silver and Gold.—Data on the effect of the impurities most likely to be present in carefully purified silver or gold indicate that the addition of 0·01% by weight of metallic impurities to pure silver, or of 0·005% to pure gold will probably not change the freezing point in either case by more than 0·1 degree.

For calibrating a thermocouple, the metal is contained in a crucible of pure graphite or other refractory material which will not contaminate the metal. Crucibles of artificial graphite about 3 cm. inside diameter and 15 cm. deep with a wall about 1 cm. thick have been found very satisfactory. The amount of metal required for such a crucible is about 1600 grams of gold or about 900 grams of silver. Silver must be protected from oxygen while hot.

The crucible and metal are placed in a furnace capable of heating the contents to a uniform temperature. The metal is melted and brought to a uniform temperature a few degrees above its melting point, then allowed to cool slowly. The thermocouple, mounted in a porecelain tube with porcelain insulators separating the two wires, is immersed in the molten metal through a hole in the centre of the crucible cover. The depth of immersion should be such that the observed electromotive force of the thermocouple is not changed by more than 1 microvolt when the immersion is increased or decreased by 1 cm. During freezing, the electromotive force should remain constant within 1 microvolt for a period of at least 5 minutes.

Freezing Point of Antimony.—The procedure in using the freezing

point of antimony as a calibration temperature is substantially the same as outlined above for the freezing points of silver and gold. Antimony has a marked tendency to undercool before freezing. The under-cooling will not be excessive if the metal is heated only a few degrees above its melting point and if the liquid metal is stirred. During freezing the electromotive force should remain constant within 1 microvolt for a period of at least 5 minutes.

Temperature of the Melting Point of Ice on the Kelvin Scale.—For the sake of uniformity, it is recommended that the value to be adopted for the melting point of ice on the Kelvin scale should be 273·15° K.*

PART IV

SUPPLEMENTARY INFORMATION

Secondary Fixed Points.—In addition to the six fundamental and primary fixed points, certain other fixed points are available and may be useful for various purposes. Some of the more constant and reproducible of these fixed points and their temperatures on the International Temperature Scale of 1948 are given in Table II. The temperatures given are those corresponding to a pressure of one standard atmosphere, except for the triple points of water and of benzoic acid. The formulae for the variation of temperature with pressure are intended for use over the range from $p=680$ to $p=780$ mm. of mercury.

Relation between the International Temperature Scale of 1948 *and the Thermodynamic Celsius Scale.*—At the time of the adoption of the International Temperature Scale of 1927, the evidence available was insufficient to establish definite differences between that scale and the thermodynamic Celsius scale. The earlier investigations, such as those which were published in 1911 by the Physikalisch-Technische Reichsanstalt, indicated no differences exceeding 0·05 degree in the range 0° C. to the boiling point of sulphur.

Recent investigations at the Massachusetts Institute of Technology indicate larger differences between 200° C. and the boiling point of sulphur. Inter-comparisons of two nitrogen gas thermometers with platinum resistance thermometers were made at 0° C., 25°, 50°, 75°, 100°, 150°, 200°, 250°, 300°, 350° C., the boiling point of mercury, 400° C. and the boiling point of sulphur. The

* This figure of 273·15° K has not been ratified by the International Committee or by the General Conference. The decision as to the value of the last decimal figure has been postponed.

differences found between t (thermodynamic scale) and t (International Scale) have been formulated as follows:

$$t\ (\text{therm.}) - t\ (\text{Int.}) = \frac{t}{100}\left(\frac{t}{100} - 1\right)(0{\cdot}04217 - 7{\cdot}481 \times 10^{-5} t).$$

The boiling point of sulphur on the thermodynamic scale was found to be 444·74° C., the results obtained with the two gas thermometers differing by about 0·05 degree.

TABLE II

Secondary Fixed Points under the pressure of one standard atmosphere (except for the triple points).	Temperature °C (Int 1948)
Equilibrium between solid carbon dioxide and its vapour	−78·5
$t_p = -78{\cdot}5 + 12{\cdot}12\left(\frac{p}{p_0} - 1\right) - 6{\cdot}4\left(\frac{p}{p_0} - 1\right)^2$	
Freezing mercury	−38 87
Equilibrium between ice, water and its vapour (Triple Point)	0 0100
Transition of sodium sulphate decahydrate	32·38
Triple point of benzoic acid	122·36
Equilibrium between naphthalene and its vapour	218·0
$t_p = 218{\cdot}0 + 44{\cdot}4\left(\frac{p}{p_0} - 1\right) - 19\left(\frac{p}{p_0} - 1\right)^2$	
Freezing tin	231·9
Equilibrium between benzophenone and its vapour	305·9
$t_p = 305{\cdot}9 + 48\ 8\left(\frac{p}{p_0} - 1\right) - 21\left(\frac{p}{p_0} - 1\right)^2$	
Freezing cadmium	320 9
Freezing lead	327 3
Equilibrium between mercury and its vapour	356 58
$t_p = 356{\cdot}58 + 55{\cdot}552\left(\frac{p}{p_0} - 1\right) - 23{\cdot}03\left(\frac{p}{p_0} - 1\right)^2 + 14\ 0\left(\frac{p}{p_0} - 1\right)^3$	
Freezing zinc	419 5
Freezing antimony	630 5
Freezing aluminium	660·1
Freezing copper in a reducing atmosphere	1083
Freezing nickel	1453
Freezing cobalt	1492
Freezing palladium	1552
Freezing platinum	1769
Freezing rhodium	1960
Freezing iridium	2443
Melting tungsten	3380

APPENDIX II

COMPARISON OF THERMOMETRIC SCALES

Centigrade and Fahrenheit

C.	F	C	F	C.	F.	C.	F.	C.	F
−20	−4·0	110	230·0	260	500	500	932	950	1742
−10	14·0	120	248·0	280	536	520	968	1000	1832
0	32·0	130	266·0	300	572	540	1004	1100	2012
10	50 0	140	284·0	320	608	560	1040	1200	2192
20	68·0	150	302·0	340	644	580	1076	1300	2372
30	86 0	160	320·0	360	680	600	1112	1400	2552
40	104 0	170	338·0	380	716	650	1202	1500	2732
50	122·0	180	356	400	752	700	1292	1600	2912
60	140·0	190	374	420	788	750	1382	1700	3092
70	158·0	200	392	440	824	800	1472	1800	3272
80	176·0	220	428	460	860	850	1562	1900	3452
90	194 0	240	464	480	896	900	1652	2000	3632
100	212·0								

Note —Each change of 10° C. is equivalent to a change of 18° F.

INDEX

Absolute zero of temperature, 5, 7, 8, 250
Accuracy, limits of, 8, 21, 22, 23, 28, 35, 40, 41, 44, 45, 55, 67, 69, 70, 71, 81, 91, 97, 102, 104, 105, 121, 153, 177, 250
Ageing of thermometer glass, 15
Air thermometer, 6
Alarm or warning signals, 133, 140, 145, 156
Alcohol, 10, 24, 28
Amplifier circuit, 161
Amyl-acetate standard lamp, 99
Annealing of thermometer glass, 15
— of wires, 67, 246
Antimony, freezing point of, 249, 251
Anti-parallax mirror, 117
Atmospheric pressure, standard, 244
Automatic controlling systems, 128–75
— potentiometer, 75
Automotive Eng, 201

Balancing coils, 50
Ballistic galvanometer, 122, 123
Barometer reading, 12
Barrier layer cell, 110
Barus, 60
Base metal thermocouples, 61
Batches, heating in, 131, 133, 153
Baths for testing thermometers, 22, 249
Beckmann thermometer, 23
Becquerel, 60
Bifilar suspension, 115
Bimetallic strip, 32, 121, 140
Black body, definition of, 78
— — enclosure, 79
Black body radiations, Stefan-Boltzmann law, 79
Boiling point of water, 3, 12, 247
— — of oxygen, 247
— — of sulphur, 33, 39, 248
Bore of thermometer stem, 16
Bowen controller, 155
Bowen Instrument Co, Ltd, 57, 58, 75, 104, 116, 155
Bride, W L, 200
Bristol Co, The, 170
Bristol, compensating leads, 68
Bristol Instrument Co, Ltd, 170
British Association, 36, 205
British Rototherm Co., Ltd, The, 32, 140
British Standard Code, 30, 121
British Standard Specification, 22, 23, 24, 25, 26
British Thermostat Co, Ltd, The, 29, 140
Brown Instrument Co, 150, 159, 168, 169, 170
Bryant, E M, 209
Buller trial rings, 179
Bureau International des Poids et Mesures, 8
Bureau of Mines, Washington, 210
Bureau of Standards, Washington, 15, 21, 40, 55, 66, 69, 81, 95, 97
Burgess and Foote, 81, 94, 95
Burstall, Prof, 235

Cadmium cell, 77
Calibration of mercury thermometers, 22
— of thermocouples, 62, 67
— of wrought-iron, nickel couple, 189

Calibration of stellite, steel couples, 227, 228
Callendar, Prof., 8, 36, 38, 39, 42, 186, 204, 205, 215, 235, 241
Calorimeter thermometers, 23
Calorimetric pyrometer, 176
Cambridge Instrument Co., Ltd., 37, 38, 43, 45, 50, 52, 61, 63, 85, 116, 117, 127, 131, 136, 137, 152
Campbell galvanometer, 114
Carnot cycle, 4
Cathode ray tube, oscillograph or oscilloscope, 124, 126, 204, 233
Centigrade or Celsius scale, 4, 243
Civil Engineers, The Institution of, 184, 187, 191, 209, 215, 219
Clark cell, 76
Clinical thermometers, 25
Clyde Fuel Systems Ltd , 174
Coal stoker, underfeed, 175
Coil suspensions in galvanometers, 113, 114, 115, 116
Coker, Prof , and Scoble, 219, 238
Cold junction compensator, 73, 119
— — corrections, 59, 67, 69
— — position, 59, 68
Compensating leads, 42, 46, 68, 69, 218
Conductivity, electrical, of flame, 150
Construction of mercury thermometer, 10
Contact maker, rotary, 124, 222
Control of temperatures, methods of, 128
Controller differential, 129, 130
— for electric oven, 132.
— — gas heated bath, 132
— — — — — lead pot, 133
— of humidity, 53, 137
—, hydrostatic, for steam valve, 134
— or regulators, 128
—, Sarco, pressure operated, 138
Controller system, The Rheostatic Co., Ltd., 144
— — Bowen Instrument Co., 155
— — Brown Instrument Co., 159
— — Foxboro Co., 172
— — Wheelco Instruments Co., 157
Controllers, general application of, 152, 173
Conversion of temperature scales, 4, 252
Corrections in gas thermometers, 8
— for impure platinum, 40
— — stem emergence, 17
Cossor double beam cathode ray oscillograph, 233
Critical temperatures and pressures, 29
Crompton, Colonel, 191
Cross-coil indicators, 48, 51, 55, 117
Cutting-tool temperatures, 228, 229

Dairy thermometers, 26
Dalby, Prof , 235
Dalton's law of mixtures, 52
D'Arsonval galvanometer, 113
Depression of zero, 14
Dial thermometer, 27
Difference formula, 39
Differential, controller, 129, 130
Diode valve or tube, 162
Disappearing filament optical pyrometer, 100
Displacement laws of Wien, 96
Distance thermometers, 49
Donkin, Bryan, 184, 215
Durston, Sir A J., 214

Economies through temperature control, 175
Einthoven thread galvanometer, 123, 226, 228
Electrical conductivity of flame, 150
— pyrometers in furnaces, 64

Electrical resistance thermometers, 36, 49, 50, 53, 170, 173, 218, 245
Electronic amplification, 75, 157, 161, 169, 170, 172
— balancing relay, 168
— circuits, 157, 158
— proportional relay circuit, 169
Electronics in industry, 159, 161
Electrons, theory of, 106, 108, 162
Elliott Brothers (London) Ltd., 53, 72, 87
Emergent stem corrections, 17
Emissivity, relative, 80, 81, 97
Engineer, The, 226
Engineering, 224
Engineers and Shipbuilders in Scotland, Institution of, 207
Errors due to dirt and moisture, 38, 44, 57, 94
— — to heating of platinum resistance coils, 55
— — to radiation, 20, 57, 79, 241
— in optical pyrometers, 104
— in thermometers, 13, 14, 15, 17, 28, 30, 31
— of radiation pyrometers, 93
—, sources of, in resistance thermometers, 55
Exchanges, theory of, 79
Expansion and contraction pyrometers, 178
External pressure, errors due to, 15, 29

Fadenthermometer, 17
Fahrenheit scale, 3
Féry radiation pyrometer, 85, 94, 95
Fire insurance, 151
Fixed points of temperature, 244, 251
Flexible capillary tubing, 28
Floating electrical control, 129
Flue gas thermometer, 19
— thermostat, 144, 174
Formulae, thermo-electric, 62, 221, 244, 245
—, platinum resistance, 39, 40, 243, 244
Foster Instrument Co., Ltd., 88, 116, 126
Foster photo-electric pyrometer, 112
Foster radiation pyrometer, 88
Four lead compensation, 41
Foxboro Co., control system, 172
Foxboro-Yoxall Ltd., 172
Freezing or melting points, 34, 244, 249, 251
— point of water, 3, 11, 244, 246, 247
Full radiations, 78
Fundamental coefficient, 39
— interval, 3, 14, 39
— zero, 39
Fusible alloys, 181, 214
Fusion pyrometers, 179, 213, 214

Galvanometers, moving coil, 113
Gas filled mercury thermometers, 25
— — photo-cells, 108
— heated bath controller, 133
— — lead pot controller, 133
— pressure thermometers, 6, 28, 31
— temperatures in cylinders, 235, 237, 238
— thermometer, constant volume, 6
Gases, laws of perfect, 5
Gear teeth temperatures, 230
General Electric Co , Ltd., 107
Gibson, Prof. A. H , 196
Glass, annealing of, 15
— suitable for thermometers, 14, 22, 23, 24, 25
Gold, freezing point, 249
Grey or selective surfaces, 80
Griffiths, Prof. 36

Haber, Dr. F., 242

Hall, Prof. E., 215
Harker, Dr., 71, 239, 240
Harris indicator, 48
Heat transfer, 82
— —, rate of, steam to surface, 204, 205, 209
— treatment of thermometer glass, 15
Heating in batches, 131, 133, 153
Herbert, E G , 227
High-low control, 129
Holborn and Day, 8
Holborn-Kurlbaum type of optical pyrometer, 100
Holman formula for e m f , 62
— potentiometer, 74
Honeywell-Brown Ltd , 88, 152, 159, 173
Honeywell system of flame control, 151
Hopkinson, Prof., 187, 237
Hoskins couple, 61
Humidity controller in timber kiln, 137
—, measurement of, 52, 137
— meter, 53
—, relative, 53
Hydrogen gas thermometer, 8
— scale of temperature, 8
Hygrometer, 53
Hypsometer, 12
Hysteresis errors, 31

Ice bobbin, 42
Immersion of stem, 17
Imperial Chemical Industries, Ltd., 182
Incubator thermometers, 26
Index or dial thermometers, 27
Indicating paints or colours, 181
Indicator, multipoint, 52
—, single-point wall pattern, 117
Indicators, high speed pressure 242
Instrumental errors in thermometers, 14
Instrumentation, 151, 152, 173, 175
Instrument Manual, The, 18, 173
Insurance companies, 151
International temperature scales, 8, 9, 12, 34, 243
— and Thermodynamic scales, relation between, 250
Ions, positive and negative, 106
Iron and Steel Inst., 110

Jena glasses, 14, 15, 26
Johnson, Matthey and Co , 62, 238
Joly meldometer, 179
Jordon, H. P , 205

Keeling and Walker, Ltd., 180
Kelvin, Lord, 4, 59
Kirchhoff, 78

Laboratory thermometers, 22
Lag of thermometer, 16, 215
Lander, Prof., C H., 82
Laws of gases, 5, 6
— of radiation, 78, 80, 96
Lead sulphide cell, 111, 231
Leads from piston, carrying of, 192, 194, 199, 201, 203
Le Chatelier, 60, 97
Leeds and Northrup Co , 47, 50, 73, 91, 93, 101, 102, 153, 154
Lens front stem, 21
Liquids for vapour pressure thermometers, 29, 30
Lummer and Pringsheim, 96

Materials used in photo-electric cells, 109
Mechanical Engineers, The Institution of, 37, 82, 181, 184, 185, 191, 193, 196, 200, 203, 205, 227, 230, 231, 235, 241 242
Meldometer, Joly, 179
Mellanby, Prof A L , 185
Melting or freezing points, 34, 244, 251
— point of ice, 3, 11, 246, 247

Mercury bulb thermometers, 27
— thermometers, 10
— — specially mounted, 20, 26
— vapour, tension of, 25
Meteorological thermometers, 24
Methods of measuring temperatures, 9
Micro-gap switches, 143
Modulating or proportional control, 130
— valve, 147
Monochromatic light, 95, 97, 98, 101, 104
Moving coil galvanometers, 113
Mucklow, Prof. G. F., 191

Nagel, Prof. A., 224
National Physical Laboratory, 9, 14, 21, 22, 23, 24, 25, 66, 67, 239, 240, 243
Nature, 231
Naval Architects, Inst., 214
Nickel, Heat contents in, 177
Nicolson, Prof J. T., 204, 205, 215

Oil burner system with forced draught, 174
On-off, two-position or two-step control, 129
Optical pyrometers, 95
— —, errors and corrections, 104
— —, Holborn-Kurlbaum type, 100
— — in use, 103
— —, with heat conductive tip, 103
— —, Wanner type, 98
Orton cones, 181
Oscillograph galvanometers, 123
— or oscilloscope, cathode ray type, 124, 126, 204, 233
Oven, electric, regulator, 132
— thermometers, 26

Paints or colours, indicating, 181
Parker, R. C., and Marshall, P.R., 231
Peake's compensating leads, 68
Peltier, 58
Pentane, 24
Philosophical Magazine, 8, 36
Photo-conductive cells, 111.
Photo-electric cells, 106, 150
— —, materials used, 107, 109
— — in potentiometer, 75
— pyrometer, Foster, 112
Physical properties of liquids, 30
Pilot thermostat, 139
Piston temperatures, 193, 195, 200, 201
Pivoted galvanometers or indicators, 115
Planck, 96
Platinum, platinum-iridium couple, 60, 241
—, platinum-rhodium couple, 60, 61
— purity of, 40, 244
— resistance thermometer, 36, 50, 218, 235
— temperature, 39
Pneumatic or hydrostatic control, 135, 170
Pockets for thermometers, 18
Polarised light, errors due to, 100
Polarising prisms, 98
Potentiometer, automatic, 75
— circuit, 45
— method of measuring e m f., 69
—, portable, 72
— system, Leeds and Northrup Co., 73
—, vernier type, 71
Pouillet, 60
Precautions, moving coil instruments, 121
Pre-ignitions, 190
Preston, *Theory of Heat*, 5, 79
Properties of matter used to measure temperatures, 9
Proportional band, 130
— control circuit, Brown, 168
— or modulating control, 130, 168

Pyrometer Instrument Co., The, 90, 102
Pyrometer, on colour basis, 104
—, thermo-electric, 58

Radiation, errors due to, 20, 57, 79, 241
— of hot gases, 81
— laws of, 78, 80, 96, 232, 233, 245
— pyrometer, Féry, 85
— —, Foster, 88
— —, mounted on furnace, 87
— pyrometers, 82
— —, calibration of, 80, 95
— —, errors of, 93
— —, fixed focus, 83, 84, 87
— —, sighted in open, 81
— —, variable focus, 83, 84, 86
Range setter, 119
Ranges of control, 153
Recorders, temperature, 126
Rectification, property of flame, 151
Rectifier cell, 110
Rectifiers, half-wave, 162
Regnault, 6
Regulating device for controllers, 135
Reichsanstalt, Physikalisch-Technische, 14, 250
Relay valve for gas regulator, 133
Re-set control, 130, 168, 170
Resistance of flames, 150
— thermometer, 36
— — coils, 37, 50, 173
— — for measuring gas or steam temperatures, 218, 225, 235, 237
— —, sources of error, 55
— —, standard, 245
— wire free from strains, 37, 245
Response regulator, 149
Rheostatic Co., Ltd., The, 33, 139, 141, 144, 147, 149
Room thermostat, 141
Royal Society, 36, 237

Sarco pressure-operated controller, 138
Sarco Thermostats Ltd., 138
Scales of temperature, standard, 3, 4, 243
Seebeck, 60
Seger cones, 180
Selective surfaces, 80
Selenium cell, 111, 156
Sheaths for electrical thermometers, 38, 50, 63, 64
Siemens, Sir W., 36
Silver, freezing point, 249
Single pivoted galvanometer, 116, 117
Six's self-registering thermometer, 24
Smith bridge, 45
Smith, Sir F. E., 45
Sources of error in resistance thermometers, 55
Standard atmospheric pressure, 244
— cells, 70, 76
Standardised lamps, 99, 105
Steam engine cylinder temperature, 184, 185, 186, 215
— valve, hydrostatically controlled, 135
Stefan-Boltzmann fourth power law, 79, 94
Stem exposure, 17
Stoker, underfeed coal, 175
Strain gauges, 37, 203
— sensitivity, 37
Suction thermometer, 57
Sulphur boiling point, 33, 248
Sulzer, R, 226
Surface temperatures, measurement of, 64, 80, 81, 91, 97, 112, 173, 184, 196, 219, 231
Suspension of coil in galvanometers, 113, 114, 115, 116
Systems of temperature control, 128

Tait, 60
Taylor-Wharton Iron and Steel Co., 175
Temperature, absolute zero of, 5, 7, 8, 250
— controllers, 128
—, cutting tool, 227
—, cyclical fluctuation of, 215, 218
—, cylinder gases, 235, 237, 238, 240
—, gear teeth, 230
— indicating paints or colours, 181
— indicator, wall pattern, 117
— —, multi-point, 52
—, International scales of, 8, 9, 243
—, petrol engines, 186, 196, 200
—, pistons, valves, etc , 187, 189, 191, 193, 195, 199, 200, 201, 227
— recorders, 126
—, steam engines, 185, 186, 215, 224
—, steel tyre, 230
Test lamps for optical pyrometers, 99, 102, 105
Testing of thermometers, 21, 22
Theory of exchanges, 79
Thermetric colours, 182
Thermistors, 57
Thermocontrol Installations Co , Ltd , 170
Thermocouple circuits in piston, 198
Thermocouples, base metal, 61
—, standard, 246
— in engines, 187, 191, 193, 196, 198, 201, 215, 217, 219, 224, 227, 238, 239
Thermodynamic scale of temperature, 4, 243
Thermo-electric formulae, 61, 244
— power, 62, 187, 221, 228
— pyrometers, 58
Thermojunctions in tubes, 205, 207, 209, 210
Thermometers, bomb calorimeter, 23
—, clinical, 25
—, encased, 19
—, errors of, 13, 14, 28
—, general purpose laboratory, 22
—, mercury, 10
—, meteorological, 24
—, pockets or wells, 18
—, Six's self-registering, 24
—, vapour and gas pressure, 28
Thermometric scales, 252
Thermopile, 60
Thermoscope, 181
Thermostat, 131, 138, 140, 141, 142
— control, 138
Thomson effect, 59
Thread recorders, 127
Three-lead compensation, 46, 47
Three-position or step control, 129
Throttling range, 130, 170
Toluene, 24, 29
Total radiation pyrometers, 82
Triode valves or tubes, 163
Triple point of water, 12, 246, 251
Two-position, two-step, or on-off control, 129

Vacuum photo-electric cell, 107, 108
Vapour pressure of mercury, 25
— — thermometers, 28
Ventilation, 151
Vernier potentiometers, 71
Verre dur, 14

Wanner optical pyrometer, 98
Water bath thermometers, 26
Watkin heat recorders, 181
Webster, G C , 207
Wedgwood contraction pyrometer, 178
Welding of thermojunctions, 66
Wengers Calorites, 181
Weston, 77

Wheatstone bridge, 42, 43, 45, 50, 55, 58, 100, 119, 131, 152, 153, 168, 170, 172
Wheelco controller system, 157
Wheelco Instruments Co , 63, 66, 150, 157
Whipple temperature indicator, 43
Wien's displacement laws, 96
Wire strain gauges, 37, 203
Wright Baker, Prof. H , 193, 196

Xylene, 28

Zero, depression of, 14
— of temperature, absolute, 5, 7, 8, 250